PB90-198748

# Pesticide Sources to the Soil and Principles of Spray Physics

(U.S.) Environmental Research Lab., Athens, GA

1990

U.S. Department of Commerce
National Technical Information Service
NTIS

## TECHNICAL REPORT DATA

*(Please read Instructions on the reverse before completing)*

| 1. REPORT NO. | 2. | 3. REC |
|---|---|---|
| EPA/600/D-90/007 | | PB90-198748 |

**4. TITLE AND SUBTITLE**
PESTICIDE SOURCES TO SOIL AND PRINCIPLES OF SPRAY PHYSICS

**5. REPORT DATE**

**6. PERFORMING ORGANIZATION CODE**

**7. AUTHOR(S)**
Chester M. Himel*, Harry Loats**, and George W. Bailey***

**8. PERFORMING ORGANIZATION REPORT NO.**

**9. PERFORMING ORGANIZATION NAME AND ADDRESS**
*Department of Entomology, University of Georgia, Athens GA 30602
**Loats Associates, Westminister MD 21157
***U.S. Environemntal Protection Agency, Athens GA

**10. PROGRAM ELEMENT NO.**
ACBE1A

**11. CONTRACT/GRANT NO.**

**12. SPONSORING AGENCY NAME AND ADDRESS**
Environmental Research Laboratory - Athens, GA
Office of Research and Development
U.S. Environmental Protection Agency
Athens GA 30613

**13. TYPE OF REPORT AND PERIOD COVERED**
Book Chapter

**14. SPONSORING AGENCY CODE**
EPA/600/01

**15. SUPPLEMENTARY NOTES**

**16. ABSTRACT**

In the past 50 years, organic pesticides have greatly enhanced the production and quality of food, feed, and fiber as well as the control of disease vectors and pests adversely affecting human health and welfare. In this review of the pesticides literature, the pesticide source term is characterized as it determines the primary and secondary pathways of transport to the soil surface. Factors influencing intra- and inter-compartmental transport are defined from a modeling perspective. Principles of spray physics are discussed, including the influence of application methodology, the influence of formulation on spray propagation, the effects of drift impingement to offsite areas, the metabolic efficacy of formualtions in killing pests. Also described are predictive models of the movement of sprayed pesticides.

**17. KEY WORDS AND DOCUMENT ANALYSIS**

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| | | |

| 18. DISTRIBUTION STATEMENT | 19. SECURITY CLASS *(This Report)* | 21. NO. OF PAGES |
|---|---|---|
| RELEASE TO PUBLIC | UNCLASSIFIED | 84 |
| | 20. SECURITY CLASS *(This page)* | 22. PRICE |
| | UNCLASSIFIED | A05 |

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

## Chapter II

## Pesticides Sources To the Soil and Principles of Spray Physics

2-1 Pesticide Entry into the Environment.

2-2 Pesticide Properties.

2-3 Formulation.

- 2-3.1 Emulsifiable Concentrates-Solution Systems.
- 2-3.2 Wettable Powders, Granular Products and Flowables.

2-4 Pesticides Application Systems.

- 2-4.1 High Volume Dilute Spray Systems.
- 2-4.2 Low Volume and Ultra Low Volume Sprays.

2-5 Foliar Application and Loss.

- 2-5.1 Initial Deposit of the Pesticide.
- 2-5.2 Pesticide Disappearance/Persistence.
- 2-5.3 Washoff - A Specific Loss Pathway.

2-6 Source Term Descriptor for Modeling.

2-7 Pesticide Source Characterization and Risk Assessment.

2-8 Principles of Pesticides Spray Physics.

- 2-8.1 Spray Propagation.
  - 2-8.1.1 Sedimentation Theory
  - 2-8.1.2 Turbulence Theory
- 2-8.2 Estimation of Droplet Size Distribution.
  - 2-8.2.1 Effects of Evaporation on Droplet Size.
  - 2-8.2.2 Extrapolation to Non Aqueous Formulations.
- 2-8.3 Stokes Law and Spray Cloud Sedimentation.
  - 2-8.3.1 Turbulent Transport.
- 2-8.4 Pesticide Spray Impingement.
  - 2-8.4.1 Spray Drift and Spray Efficiency/Efficacy.

2-9 Properties of the Canopy Environment on Spray Interaction.

- 2-9.1 Physical Properties of Canopy.
- 2-9.2 Micrometeorological Factors.
- 2-9.3 Spray Delivery to Canopy.

2-10 Case Studies on Pesticide Spray Transport.

2-10.1 Methods to Measure Pesticide Spray Transport.

2-10.2 Case Studies.

2-10.2.1 Scottish Forestry Service Case Study.

2-10.2.2 Canada Case Study.

2-10.2.3 United States Case Study - 1.

2-10.2.4 Canada-USA Case Study - 2.

2-10.2.5 United States Case Study

2-10.3 Summary

2-11 Modeling Pesticide Spray Application.

2-11.1 FSCBG Model.

2-11.2 AGDISP Model.

2-11.3 Picot Model.

2-11.4 EPAMS Model.

2-11.5 Reid and Crabbe Model.

2-11.6 FWG Model.

2-11.7 Bragg Model.

2-11.8 Miller Model.

2-11.9 Trayford and Welsh Model.

2-11.10 The Cranfield Model.

2-11.11 Loats/APHIS Model.

2-12 Research Needs.

2-13 Conclusions.

2-14 References.

In the past 50 years, organic pesticides have greatly enhanced the production and quality of food, feed, and fiber as well as the control of disease vectors and pests adversely affecting human health and welfare. Specifically, pesticides have been used in agriculture to increase productivity and the quality and quantity of food, feed, and fiber; in forestry for pest control in silviculture; in the industrial, commercial, municipal, and military sector for rodent and weed/brush control around plant sites and in right-of-ways; in medical vector control to reduce the numbers of mosquitoes, etc.; and in the urban environment for termite control in structures and pest control in gardens. For example, more than 500 different formulations of pesticides are usen in the urban environment and in excess of 11,363,636 kg (25 million pounds) of active ingredients are used in the gardens, yards and homes annually in the United States (USEPA, 1979). Agriculture represents the largest single market for pesticides.

The purpose of this chapter is to review the literature in order to (i) characterize the pesticide source term as it determines pesticide transport to the soil surface, which involves both primary and secondary pathways of transport to the soil; (ii) define factors influencing intra-and-intercompartmental transport; (iii) define the source term from a modeling perspective; (iv) discuss principles of spray physics (influence of application methodology, formulation on spray propagation, drift impingement to offsite areas, and metabolic efficacy in killing pest); and (v) describe predictive models of spray movement.

## 2-1 PESTICIDE ENTRY INTO THE ENVIRONMENT

Pesticides may be introduced directly into the environment in a liquid phase, as a dispersion or solution, or in the solid phase, as a powder, dust, microcapsule or granule. Sprays are directed to foliage or to the soil or are applied stoichastically to these same media as rainout (Fig. 2-1 and 2-2). Solids are applied directly to the soil surface, or to foliage. Pesticides also may be incorporated directly into the soil, usually in the top few mm to exert a biological effect. A pesticide also may enter the environment as a result of accidental spill or malicious application for waste disposal purposes.

Environmental entry and transport processes can occur either between or during a rainfall event. Those direct or primary transport processes to the soil surface that occur during a rainfall event include wet deposition and foliar washoff. Secondary transport processes to the soil surfaces that occur between rainfall events include spray drift and dry deposition. (The source term is particulates emanating from the pesticide drift process and pesticide found on dust particles generated by wind pickup and atmospheric transport.) Pesticides dissolved in atmospheric water vapor may be deposited either on the soil surface directly or indirectly to the foliar surface with subsequent removal during rainfall events via the process of foliar washoff. Therefore, pesticide sources to the soil surface include application events, atmospheric wet or dry deposition, foliar washoff, or accidental spills onto the soil surface or into the soil profile. Environmental sinks for pesticides include chemical, photochemical and biological transformation, volatilization losses, erosion and runoff; leaching; harvest removal and storage.

The mass balance is given by

$$\underline{\text{Pesticide Application}},\ \text{kg ha}^{-1} = \Sigma\ \underline{\text{Pesticide Sinks}}$$

[ Chemical, photochemical, biological, and volatilization losses + Erosion + Runoff + Leaching + + Harvest + Storage (surface, upper and lower zone) (Bailey et al., 1985)]

Pesticides are applied directly to the soil as (i) preplanting treatments; (ii) pre-emergence treatments; (iii) postemergence treatments; or (iv) soil sterilants. Several factors influence the final concentration of soil-applied pesticide including: volatilization, photochemical degradation, chemical and biological transformation, leaching, and sorption. The initial pesticide source location, i.e., foliage or soil surface on day of application, depends upon the pest being controlled, pesticide concentration and formulation, and the mode of application. From a mass balance modeling standpoint, it is imperative to know at the time of application the pesticide concentration on the soil surface, plant canopy, or plant residue surface ( or, if incorporated, the depth of incorporation). The knowledge of the initial concentration of pesticide in the applicator tank is not sufficient as up to 60 % of the applied tank concentration (Smith et al., 1976) may be lost through spray drift and volitilization. Secondary transport processes include foliar washoff, foliar drip (occurring on application day), rainout, and volatilization from foliar and soil surfaces. The concentration of pesticide available for transport is determined by the time-varying processes/sinks including biotic/abiotic transformation, volatilization, plant uptake, plant harvest (root and foliar absorption), leaching, and foliar residue washoff. These sources and major transport processes can be seen in Table 2-1. The

major pesticide sources for "offsite" transport include plant residue,soil surfaces, root or grain materials, foliage (for dissolved pesticide runoff), eroded soil particles (for sorbed pesticide), granules, dust or microcapsules, and leachates (for pesticide dissolved in solution or bound to colloidal particles).

## 2-2 PESTICIDE PROPERTIES

Traditionally in a presentation on pesticide properties, an extensive discussion would focus on the major families and classes of pesticides -- specifically their structures and their specific physical and chemical properties. However, because of a proliferation of classes of pesticides over the years, this is not practical for purposes of this review. The reader is referred to a variety of references on the structures and physical and chemical properties of specific pesticides -- insecticides (Brown, 1951; Metcalf, 1955; Kubr and Poogh, 1976), herbicides (Kearney and Kaufman, 1975, 1976; Klingman and Ashton, 1982; Weed Society of America, 1983), and fungicides (Torgeson, 1969; Luken, 1971; Marsh, 1972, Sharville, 1979).

Beacuse we are interested in pesticide source characterization -- transport, transformation, and behavior to, within, and from soil, insight into important chemical characteristics is imperative. Chemical characteristics that influence pesticide transport to and from soil include (i) ionic state (cationic, anionic, basic, or acidic); (ii) water solubility; (iii) vapor pressure; (iv) hydrophobic/hydrophilic character; (v) partition coefficient; and (vi) chemical, photochemical, and biological reactivity (Bailey et al., 1985).

Over the last 10 to 15 yrs, the general characteristics of pesticides have changed drastically. The use of extremely low water solubility, strongly sorbed (extremely hydrophobic and with a very high partition coefficient), and non-mobile formulations has changed to application of materials that are more water-soluable, only slightly sorbed (more hydrophilic and lower partition coefficient value - a $K_d$ of 1 or less ), and more mobile (Carsel and Smith, 1987). Part of this change is response to environmental problems (bioaccumulation and magnification) associated with earlier formulations and the increase pest resistance to chlorinated hydrocarbon pesticides.

Pesticide properties combined with the amount of pesticide applied and entering the environment determine how much pesticides can be transported along each route from source to receptor. (Specific routes can be seen in Fig. 2-1 and 2-2.) Possible intra-compartmental transport routes include foliar washoff to the soil surface, infiltration, percolation, and movement to lower storage zones and finally to ground water. Possible inter-compartmental transport routes include overland flow; interflow to subsurface water; and direct loss to the atmosphere from the soil, subsoil or foliar surfaces or losses due to movement of sediment-bound pesticide (both water and wind modes of transport) (Bailey et al., 1985).

Sorption processes determine the relative distribution among the vapor phase, the solution phase, and the surfae-bound phase; this distribution dictates the primary or secondary transport routes.

Environmental persistence in the soil is related to the individual pesticide's properties. A persistent compound dose not hydrolyze or biodegrade readily (first-order transformation rate constant is $< 0.02$ day$^{-1}$), has a loe volatilization or Henry's law constant, has a high partition coefficient and

has a high potential to move to and contaminate ground water (Carsel and Smith, 1987). A nonpersistent pesticide hydrolyzes and/or biodegrades readily (first-order degradation rate in soils at least 0.02 $days^{-1}$), has a low Henry's law constant, is highly water-soluble, (partition coefficient $K_d < 1$), and has an appreciable mammalian or phytoxicity value.

## 2-3 FORMULATION

Technical pesticides (90+ % active ingredient) generally are formulated prior to use except when they are liquids that can be sprayed neat (undiluted). Formulations include solutions, suspensions, powders, granules, or other forms designed to meet application needs and use requirements.

Van Valkenburg (1973) notes that several factors should be considered in formulation chemistry including (i) importance of the solubility parameters of the hydrophobic and hydrophilic portion of the surface-active agent in selecting an emulsifier, (ii) effect of the phase inversion temperature on emulsion stability, (iii) the dehydrating effect of fertilizer salts and emulsifiers and the resultant stability or unstability of the emulsion, (iv) the all important flowability property of a mixture as it relates to the development of a dry pesticidal formulation, (v) catalytic effect of clays and other carriers on pesticide degradation, and (vi) and the physical properties of formulations and how they affect the size of the particles in a spray and the movement of the particles in air.

The physical and chemical properties of the formulation and its resultant spray characteristics as indicated by particle size and surface properties (surface tension, spreading coefficient and contact angles) dictates whether the pesticide will adhere to the plant surface and penetrate

pesticide formulation types are wettable powder (WP), emulsifiable concentrate (EC), water miscible concentrate (WMC) and flowables (F). These are designed to be diluted with varying ratios of water and applied by various types of spraying equipment. Important properties of the active ingredient that affect its alternate formulation include physical states, water/oil solubility, miscibility, dissolution rate, melting point, density, and physical chemical stability to heat, oxygen, and moisture (Van Valkenburg, 1973). The pH both in the bulk and in solution/suspension of pesticide formulations is also important with mixtures of pesticidal ingredients or sometimes even with a single ingredient with additives to achieve desired physical properties, ease of application, and favorable metabolic efficacy. Formulation character affects stability of the active ingredient, ease of field mixing, bioavailability of active ingredient to the target organism, residuality of active ingredient and adducts, and potential side effects of pesticides. Certain aspects of pesticide formulation and use are subject to regulation by EPA and other government agencies.

Pesticide formulations are available in many forms permitting the use of a variety of equipment types -- ground vs. aerial application -- to control target organisms effectively and successfully. Pesticides are formulated rather than used directly because of the necessity (i) to dilute high-potency material to field concentration, and (ii) to apply them to a location where the target organism can be controlled while side-effect damage to humans, plants, wildlife, and the environment is minimized.

### 2-3.1 Emulsifiable Concentrates-Solution Systems

Most pesticides are dissolved in suitable oils or other organic

solvents, with emulsifiers added, and packaged as emulsifiable concentrates (EC). Typical EC formulations contain from 0.12 - 0.48 Kg active pesticide per liter (1-4 lbs $gal^{-1}$). Solution systems without emulsifier also are used, particularly for low-volume (LV), or ultra-low-volume (ULV) sprays. Emulsifiable concentrates are the bulwark product for pesticide sprays. They can be diluted with water and are simple to use. Low surface tension increases ease of atomization and impingement probability.

### 2-3.2 Wettable Powders, Granular Products, and Flowables

Wettable powders are produced by adsorption of technical pesticides on finely ground clay containing wetting agents. The resulting products are dispersible in water. Granular products containing a very high percentage of active ingredient have been formulated to alleviate some of the problems that occurred in handling wettable powders. Flowable products are finely ground, insoluble active ingredients suspended in oils with emulsifiers. They are non-dusting and can be pumped as viscous liquids.

Granular pesticides are pellets or grains containing the pesticide diluted to the permissible concentration by mixing with other inert and functional ingredients. Granular carriers are inert, sorptive particles with a size range of 4 to 200 mesh and are produced in two forms -- disintegratable (regular volatile material - RVM) and nondisintegratable (low volatile material - LVM) in water. The major advantages of granular formulation over dusts, wettable powders, water-soluble powders and liquids are that it (i) permits uniform application at desired rates, (ii) provides minimum dusting, (iii) delivers toxicant to desire location, (iv) either water disintegratable or nondisintegratable, (v) minimizes phytotoxicity, and (vi)

regulates pesticide release so to act as a reservoir to extend pesticidal activity for a longer period of time. Granular pesticides applied to the soil surface can be picked up and moved in overland flow offsite as a result of a high intensity rainfall event (Bailey et al., 1974).

Ground applicators for granular pesticides usually are attachments on row crop planters. They include capability for application in the seed furrow or a broadcast band over the row that either remains on the soil surface or is incorporated by some mechanical means. Effective operation requires that the applicator meters, delivers, and then distributes the pesticide granule over the soil or in some cases to incorporate them to the proper soil depths.

The granules generally are metered either through a gravity-fed metering orifice or through a positive metering device in which a constant granule volume is metered by a rotor. The granule is delivered to the target location by mean of gravity or pneumatic pressure.

## 2-4 PESTICIDE APPLICATION SYSTEMS

Most pesticides are applied by spray processes whose atomization (spray spectra) is dependent on nozzle type, pressure throughput, and other factors. Dusts are no longer widely used. High technology and engineered delivery systems need development, such as for controlled release (CR) of the active agent. In Australia, a new CR product emits a biodegradable, short-life insecticide within the root system of sugarcane (*Saccharum officinarum*) (McGuffog et al., 1984). It protects the first and successive rattoon crops up to 4 yrs. This delivery system meets a critical plant protection need, is highly efficient in pesticide delivery, minimizes ecosystem effects, and limits the build-up of resistance.

### 2-4.1 High Volume Dilute Spray Systems

High volume dilute sprays in the range of 400-3000 L $ha^{-1}$ (100-800 gal $acre^{-1}$ ) are inefficient and labor and energy intensive. They operate by attempting to saturate foliage, often using turbulent, high velocity air streams. Large losses occur to the soil and to drift.

### 2-4.2 Low-Volume and Ultra Low-Volume Sprays

Spray volumes in the range of 4 to 40 L $ha^{-1}$ (1-10 gal $acre^{-1}$) are often referred to as low volume (L). Ultra-low-volume (ULV) sprays produce < 2 L $ha^{-1}$ (<0.5 gal $acre^{-1}$). These low volumes spray clouds reduce foliar runoff (foliage saturation). No low volume or ultra-low-volume spray, however, can provide "even coverage". Visual observations during spray application are widely believed to substanciate "even coverage" but have no actual validity. "Even coverage" is a visual illusion. Measurement of the actual coverage of typical foliage systems is complex and time consuming. It requires use of tracer sampling and analysis systems that meet suitable probability standards. In the case of foliage systems that have substantial vertical dimensions, i.e. forests and dense crops, deposition within the canopy falls to a few droplets per square centimeter. Transport and impingement in foliage from L and ULV sprays reflect turbulence within the canopy, the number of droplets in each size category, velocity of travel, geometry of the target, spray volume, foliage density and dimensions, and other factors. In typical cases, deposition is greatest on the tops of leaves or needles, on leaf hairs or insect setae, and on rough surfaces including leaf veins and insect appendages. Deposition on the underside of leaves is very low but increases

as turbulence increases. Insects and disease vectors that are resident on the underside of leaves represent a major pest management problem. In dense foliage, pest management often requires an increase in numbers of effective sized droplets. Specialized formulations may be required to maximize adherance and control on waxy surfaces.

The ULV sprays are increasing in use. The concept of ULV was developed to meet spatial and temporal problems in control of the desert locust during its migrational flights in inter-continental space measured in thousands of $km^3$ (Sayer, 1959). Numbers of droplets in a spray are an inverse cube function of size; hence, as spray volumes were reduced to meet logistic requirements, small size spray spectra were crucial. The original ULV concept involved a concomitant decrease in size of spray spectra and the volume of the spray; however, the significance of the size of the spray spectra was lost as ULV was adapted to agriculture using hydraulic nozzles.

As spray clouds diffuse, the numbers of droplets per $cm^3$ decreases, but lethal deposits can occur on insects when concentration of the pesticide in each droplet is high (Keathley, 1972; Himel, 1974). Volume-concentration factors in the design of insecticide spray programs are discussed by Spillman and Joyce (1978). Factors that control spray efficiency are discussed in sections 2-9 and 2-10.

Mosquito abatement groups have used ULV sprays for decades with typical applications of 60-120 mL of concentrated or neat insecticide per ha (1-2 oz $acre^{-1}$). Mosquito sprayers use special nozzles (centrifugal and pneumatic) that are designed to limit the production of droplets larger than 40-50 $\mu m$. Size specifications for pesticide sprays to meet public health needs are not in controversy. The size of aerosol droplets impinging on mosquitoes has been

reported by Lofgren et al. (1973) to center in the 5-10 μm range, conforming to impingement dynamics on a small, flying insect.

## 2-5 FOLIAR APPLICATION AND LOSS

Foliage or plant canopy may be the desired initial and final site for pesticide delivery. Plant canopy, as seen in Fig. 2-1 also may be the source of further pesticide transport to the soil or to the atmosphere. The latter may affect worker reentry and impose a human health risk. Characterization of this sink-source is necessary but has been lacking. Prediction of delivery and redistribution of pesticides within the plant canopy is the key to efficient use of pesticides. It requires a knowledge of pesticide spray physics, aerial transport phenomena, foliage intercept factors and storage; decay/transformation, plant uptake, and volatilization; and washoff behavior.

### 2-5.1 Initial Deposit of the Pesticide

Several factors influence the amount of initial deposit on the crop cover after application (Ripley and Edgington, 1983). The rate of application is the most obvious factor with increasing deposit occurring with increasing application rate. A limit is reached, however, beyond which no pesticide can adhere to the foliar surface. The amount of the deposit is slightly affected by the height of the spray boom above the canopy surface; a slightly lower amount of residue is found in the middle compared to the top of the plant canopy. The extent of ground cover is important, but plant surface characteristics, morphology, and surface area/plant mass ratio of the crop intercepting the pesticide spray also can result in a differential deposition over the crop. Formulation also affects residue deposit, and in most cases, a

lower amount of residue is found with wettable powders compared to emulsifiable concentrates or flowable formulations. Formulations may facilitate greater penetration, reduce early physico-chemical loss, and enhance foliar persistence. The amount of pesticide intercepted by the crop canopy is assumed to be proportional to the extent of ground cover at the time of pesticide application (Beyerlein and Donigian, 1979).

### 2-5.2 Pesticide Disappearance/Persistence

Persistence in this case is defined as the residence time of a pesticide in a defined compartment of the environment expressed in units of time relative to a bench mark (Greenhalgh, 1986). Pesticide persistence is the integrated effect or weighted summation of all the transformation and loss processes including chemical (e.g. hydrolysis), photochemical, and biological transformation; volatilization; cuticle adsorption; and washoff. Factors influencing persistence or the converse disappearance include crop factors (morphology, cuticle characteristics, stage of growth at treatment, and rate of growth) pesticide characteristics (Henry's law constant; water solubility; susceptibility to physical, chemical, and biological transformation processes) and environmental (rainfall intensity, duration and frequency; wind velocity; humidity; temperature; light-intensity; and percent cloud cover) conditions.

Disappearance curves after foliar application show an exponential decline for most pesticides. Pseudo first-order reaction kinetics may often be used to describe the decline in pesticide residue. One problem is that many such studies only treat a portion of the disappearance curve (time > 1 day) or only 1 to 2 half-life periods (generally five half-lives or more are preferred). Several mixed-order rate equations may be operating simultaneously because several different processes are involved and bi- or

trilinear curves have been reported (Ebeling, 1963). Many studies have failed to account for either the large initial residue loss (possibly because of volatilization, hydrolysis, or photolysis) in the early period after deposit ( time < 1 day) or the apparent long persistence of low concentrations of pesticide in the plant. The application of regression analysis using semilog first-order approaches has not resulted in good correlation, particularly where two or more apparent first or even second-order processes are involved.

For the persistance of certain pesticides in plants Sirons et al. (1982) found a relation of C = k ( a * b * log t ) , where *k* = rate of disappearance, *t* = time after application and *a* and *b* are coefficients.

### 2-5.3 Washoff - A Specific Loss Pathway

Attempts have been made to study and, in certain case, to model the various dissipation or attenuation pathways. Washoff as an attenuation pathway will be discussed; little is known about the other pathways.

Several different approaches have been reported (Beyerlein and Donigian, 1979; Smith et al., 1981; and Willis et al., 1982) for describing the foliar washoff process for any rainfall event; the form generally is PWO = FP * WOC * R where : PWO = pesticide washoff ($MT^{-1}$), FP = foliage pesticide ($ML^{-2}$) i.e. kg $ha^{-1}$, WOC = washoff coefficient ($L^{-1}$), and R = rainfall ($LT^{-1}$). Several models have been proposed to account for or predict foliar washoff. Beyerlein and Donigian (1979) proposed an equation which describes the removal of pesticides from crops by rainfall as an exponential function of the rainfall intensity. Such an approach necessitates the use of hourly rainfall data and a crop constant based on crop and pesticide properties to determine the washoff coefficient. A foliar washoff algorithm is contained in the CREAMS model

(USDA, 1980) for predicting the proportion of pesticide lost from foliar surfaces. The residue is partitioned into dislodgeable (available for washoff) and non-dislodgeable fractions. Washoff is calculated for each rainfall incident from the dislodgeable fraction, less the amount attenuated, after a plant washoff threshold has been reached. The washoff threshold (0.1 - 0.3 cm) is the amount of rainfall that a plant canopy can intercept and store prior to washoff. Smith and Carsel (1984) proposed a pesticide washoff model (FWOP) which requires daily rainfall amounts (cm $day^{-1}$) and a lumped first-order rate constant for foliar transformation processes ($k_f$). Specific formulation includes:

$$\frac{d[FP(t)]}{dt} = - k_f FP(t) - PWO(t) + APP(t) \qquad [1]$$

where

$\frac{d[FP(t)]}{dt}$ = rate of change of pesticide on foliage

$k_f$ = first-order degradation rate constant on the foliage ($T^{-1}$)

$k_f = k_p + k_r + k_b + k_v + k_h$

$k_p$ = rate constant for photolysis ($T^{-1}$)

$k_r$ = rate constant for chemical reactions

$k_b$ = rate constant for biodegradation

$k_v$ = volatilization rate constant

$k_h$ = hydrolysis rate constant

and $PWO(t) = FP(t) * WOC * R(t)$ [2]

where

PWO(t) - pesticide washoff ($MT^{-1}$)

FP(t) - foliage pesticide ($L^{-1}$)

WOC - washoff coefficient ($L^{-1}$)

R - rainfall ($LF^{1}$)

and APP(t) - application rate ($MT^{-1}$)

This equation cannot be solved analytically in a closed form because rainfall is stochastically variable in time. The equations therefore must be solved numerically as a part of a continuous simulation model. The FWOP model has been coupled with the Pesticide Runoff Simulation (PRS) (Computer Sciences Corporation, 1980) to make such calculations.

Willis et al. (1982) found that total storm losses from toxaphene on cotton (Gosspium hirstum) under simulated rainfall were independent of intensity when 24 mm of simulated rainfall was applied at the rate of 13, 25, 51, or 100 mm $h^{-1}$ just 2 h after toxaphene had been applied at 2.24 kg $h^{-1}$. Approximately 5 to 10% of the toxaphene was washed off depending upon the initial load. Linscott and Hagin (1968) reported that mean losses of sprinkle-applied 2,4-DB were 21, 60 and 93 % of the amount on or in the plant when 2, 5, 13, and 51 mm of rain were applied, respectfully. A paucity of information exists on the loss of pesticides on foliar surface because of photolysis, volatilization, chemical, and biological transformation. Research is urgently needed to define those processes and pathways both to improve model formulation and to identify sources for pesticide availability in making risk assessment.

## 2-6 SOURCE TERM DESCRIPTOR FOR MODELING

A quantitative definition of the source terms is needed for modeling pesticide exposure and for making risk assessment. A general approach described by Bailey et al. (1974) will be updated and used to quantify the pesticide source term. The initial consideration in the description of the source term is the physical state of the pesticide and its spatial distribution with respect to the soil surface. Figure 2-1 shows that it may be (i) on the foliar surface, (ii) on the soil surface or (iii) incorporated into the soil and residing in the upper storage zone. The physical state of the pesticide is determined by the nature and properties of the formulation. Pesticide formulations as discussed earlier consist of five different physical types: solutions, wettable powders, emulsions, dusts and granular pellets. Their physical-chemical composition varies with the type and initial concentration of pesticide, solvent, surfactants/wetting agents, sticking agents, particle size distribution of the dust or wettable powder, and rate of release from the granular pellet. These factors influence pesticide-soil interactions and equilibria in the various storage zones and directly affect the availability of the pesticide for surface and vertical transport as well as its susceptibility to various transformation processes.

The source definition requires that the initial pesticide phase and spatial distribution condition as dictated by the application methodologies be categorized and quantified. Pesticides are directly applied to (i) the soil surface, (ii) incorporated into the soil, or (iii) purposefully or accidentally sprayed, dusted, or applied as granules/pellets to the canopy or to crop residues. Because of the restricted mobility of the pesticide, its initial placement is a crucial factor in mathematically describing the pesticide distribution on the foliage or pest surface, and on/or throughout

the soil profile, not only before and during the first rainfall event, but also between subsequent events. The initial placement also determines the relative importance of the four modes of transport - (i) mass transfer of the pesticide in the moving liquid boundary ; (ii) pesticide desorption into or towards the moving liquid boundary; (iii) stationary dissolution and transfer to the moving liquid boundary; and (iv) moving dissolution in the moving liquid boundary -- into runoff water. Initial placement determines whether the source is planar (initially surface-applied or subsequent foliar washoff onto the soil surface) or volumetric in nature (incorporated). Depth of incorporation and homogeneity of mixing (influenced by type of incorporation tool used) also influence the effective source concentration.

In the case of either directed or accidental foliar application the soil source term description is further complicated because of such processes as foliar interception, direct foliar drip, delayed foliar washoff and the various transformation processes - photolysis, chemical ( e.g. hydrolysis) and biological -- volatilization, and plant or pest uptake and metabolism prior to reaching the soil surface. The role of atmospheric source characterization as a transport media is reviewed by Medved (1975). Pesticides released in the environment via spraying -- either aerially or via ground sprayers - pass to the target plant, pest, or soil, but some are carried away by the wind both horizontally and vertically for varying distances. These offsite sprays may either settle upon the soil surface or be deposited in rainfall (Fig. 2-2 -- secondary transport processes ).

Gohlich (1983) defines the key features of the pesticide application distribution systems which need to be considered in reducing the amount of drift to include spray atomization and transport distance between atomizer and

receptor area. Atomization is influenced by physical properties of the liquid, types of nozzle, and the atomization process. Transport is influenced by air turbulence, size of particle, evaporation behavior of the liquid particle, direction and force of the flow stream and particle motion, and forward speed of the spraying device. Drift and deposit are influenced by structure of the plant or receptor and its density and by turbulence within the canopy. The latter is related to external wind velocity.

## 2-7 PESTICIDE SOURCE CHARACTERIZATION AND RISK ASSESSMENT

Risk assessment is a tool used to evaluate the probability of an adverse impact that a pesticide, being a toxic or hazardous chemical, may have on human health or the environment. The key role that a knowledge of the physical state of the pesticide and its spatial distribution with respect to the soil surface can be seen in Fig. 2-1. The role of management practices on pesticide transport and transformation can be seen in Fig. 2-2 and 2-3. These interactions determine which environmental pathways are crucial to the estimation of both human and biological exposure and the calculations of environmental risk. This topic is discussed at greater length in Chapter 13.

## 2-8 PRINCIPLES OF PESTICIDE SPRAY PHYSICS

The developing science of pesticide spray physics is concerned with the complex interactions of spray droplets in a spray cloud and during impingement. These interactions occur (i) during transport in the air (includes both turbulent transport and sedimentation ; (ii) at the foliage-air interface (includes impingement probability and impingement filtration; and (iii) within the canopy (includes impingement probability, target geometry,

turbulence within the canopy, and impingement delivery).

Droplet impingement involves (i) size of the droplet, (ii) velocity of travel, and (iii) geometry of the substrate. A droplet large enough to have a critical impingement velocity of zero (impingement probability = 1) will impinge on a target of any geometry at zero velocity. Penetration into a foliage canopy requires an impingement probability < 1.

The hydraulic nozzle is used in most aerial and ground spray equipment because it is cheap, widely available, and because there has been no substantial pressure for change to more efficient delivery systems. Hydraulic nozzles atomize spray liquids into thin sheets and filaments and subsequently into a random, polydisperse spectrum of droplets whose sizes range from submicron to large. The distribution frequency approximates a bell-shaped, gaussian curve. A significant portion of the pesticide controversy stems from the fact that these large-droplet, broad spectrum sprays are grossly inefficient in transport of pesticides to target foliage. Its inefficiency and environmental costs are not widely recognized. Spray physics evaluates the transport and impingement characteristics of each size class of droplets in a polydisperse spray cloud. For all practical purposes, spray spectra can be divided into two size classes:

(i) Small droplets ( < 100 - 150 $\mu$m diameter).

(ii) Large droplets ( > 150 $\mu$m diameter, ranging to 400 - 600 + $\mu$m).

The significance of these two size classes is that small droplets as a class are transported primarily on turbulent eddies and have an impingement probability < 1. Their impingement on target systems depends on droplet size, travel velocity and the geometry of the target. On the other hand, the

primary force acting on large droplets is gravity. They have an impingement probability P = 1 and impinge on the first solid or liquid substrate in their flight path. Typically, this means that they are delivered to peripheral foliage or the ground.

The objective of most pesticide spray applications is to deliver the spray cloud to a foliage target. Herbicide sprays are directed at any portion of the target plant whereas most insecticide and fungicide sprays are directed at microhabitats within the foliage canopy. Spray clouds are difficult to measure and portions of the spray are invisible. An empirical spray technology based on the use of polydisperse sprays was developed in the early and middle decades of the 20th century. It was "successful" and appeared to be "simple". It was buttressed by the visual illusion that spray clouds "fell" into the foliage. The actual interaction of spray clouds with the foliage canopy and the mechanism of pest control from sprays was unknown. This conventional spray technology was developed in an analytical void since nanogram sensitivity gas chromatography (GC) was not developed until 1959 and analytical methods for spray mass transport were not developed until the late 1960s. Spray physics became a part of pesticide controversies only in the decades since 1970.

In this part of Chapter 2 we will discuss at length the role of mass transfer as the initial step by which pesticides are introduced into the environment. This is a different approach from those which relate to the study of pesticides <u>after</u> their original transfer. Controversies focus on the significance of droplet spectra in spray clouds, the mechanism of delivery of sprays, effects of a foliage environment, pesticide volatility, redistribution, and spray drift.

Spray physics provides one simple, overriding guide to pesticide use -- efficient delivery of pest management sprays is size-limited. This is because foliage systems present a narrow, size-limited "window of opportunity" for pesticide sprays. The upper size limit is determined by impingement on peripheral foliage and the lower size limit by impingement probability within the canopy. All broad spectrum sprays overlap that window and are therefore "successful", whatever may be their economic and ecological limitations.

2-8.1 Spray Propagation.

Mass transport and impingement can now be measured for all discrete spray droplet spectra which travel as a spray cloud. This includes spray clouds which are electrostatically charged but excludes chemigation and high volume sprays which saturate and "run-off" from foliage. As spray clouds move away from their source, they expand as droplets within the cloud and are subjected to turbulence and gravitational forces. Turbulence is a key factor in the transport of "small" spray droplets. Large droplets and light refraction allow spray clouds to be seen. Under typical spray conditions turbulence and sedimentation causes the spray cloud to move in an expanding, usually downward pattern.

Although it is well known that the ground under a tree remains dry after a "light rain", the "light rain" of a pesticide spray at the foliage-air interface is assumed to "penetrate" and to provide "even coverage" within the foliage canopy. Although nature had provided a clue in the size-related transport and impingement of air-borne pollen and although the engineering physics of air filtration of particulates was well known, no interdisciplinary transfer of physical principles occurred and spray physics played no part in

an empirical, simplified, conventional spray technology which was accepted worldwide without any analytical basis.

To some significant extend this is because of spray drift. Spray drift is a fact. However it typically constitutes < 5% of the mass of most sprays and is dwarfed in potential ecological significance by losses (60-80%) of most pesticide sprays on peripheral foliage or to the ground (Table 2-6). The direct effects of spray drift can be seen. The ecological and economic significance of pesticides wasted and transferred to the soil, is difficult to measure or assess.

The typical assumption of spray drift is that it stems from downwind transport of "small" droplets in the spray cloud outside the spray area. Volatility, evaporation, and secondary transfer effects are not considered. The ubiquitous presence of "small droplets" in the foliage canopy was unknown or ignored. Analytical proof of the delivery of "small" droplets into foliage canopies is the crux of the analytical data provided in the case studies in this chapter. These case studies require some knowledge of spray spectra. Spray spectra measurements include:

$D_{max}$ - the diameter of the largest droplet in the cloud, as estimated.

*MMD (VMD)* - the mass median diameter (volume median diameter). The diameter that separates the spray (mass or volume) into equal parts.

*NAD* - number average diameter, the average size of all spray droplets measured.

Most pesticide sprays have a $D_{max}$ of 300 - 600 $\mu$m with a concomitant MMD in the range of 125 - 400 $\mu$m. Broad spectrum herbicide sprays have a $D_{max}$ of

1000 μm or more. Grover et.al. (1972) and Barry (1984) have reported on the distribution of sizes in sprays.

Pesticide spray transport and impingement is controversial. Two theories (sedimentation theory and turbulence theory) have been used to explain the effects of pesticide sprays. The multibillion pound pesticide spray industry is largely guided by sedimentation theory. Turbulence theory was developed after 1970. It represents a basis for optimization of pest management and risk management of drift. The two theories diverge in their predictions as to the bioefficacy of large-size and small-size portions of spray clouds. In this divergence, the theories are mutually exclusive; both cannot be correct. The case studies cited in this chapter provide an analytical basis for turbulence theory. A brief review of sedimentation and turbulence theories is given below.

2-8.1.1 Sedimentation Theory

Sedimentation theory is empirical and has no rigorous analytical basis. It evolved prior to development of analytical systems for mass transport of sprays. Its primary concept is Stokes Law of Falling Spherical Bodies and a Reynolds number $< 0.1$. It assumes that gravitational forces are predominant even in a cross wind. Some of its concepts are depicted in Figure 2-5. "Small droplets", having minimal mass are assumed to travel "an infinite distance." If "small" droplets "blow away", large droplets must then provide the pest management which is observed. Actually impingement probability limits spray droplet access in and on foliage systems and thus the validity of sedimentation theory.

The theory gained credibility because of the visual illusion of spray clouds "falling" into foliage systems. The drift problem reached a critical stage in the use of herbicide sprays and was solved by the use of "ultra large" spray spectra with a $D_{max}$ as much as 1000 $\mu$m without recognition of transport inefficiency and ecological effects. As an empirical theory, it has no analytical base and is an anachronism in a scientific century.

2-8.1.2 Turbulence Theory

Turbulence theory stems from principles of spray physics and the mass transfer analytical data presented in the case studies in this chapter. The theory assumes that mass transport of spray droplets in a spray cloud is the vector resultant of turbulence and gravitational forces. As droplet size decreases, the contribution of turbulent forces increases. Transport and delivery patterns of spray droplets in spray clouds are determined by turbulent diffusion and sedimentation. Spray droplets move in envelopes of sizes determined by the extent of turbulent forces (Fig. 2-4). Spray efficiency and spray drift are inversely related dependent variables. Spray efficiency is a determinant in risk management of drift.

The key to efficient pest management lies in favorable turbulence and optimization of the size of the spray spectra used. Data for optimum spray droplet sizes are found in the case studies cited in this chapter. Computer-aided spray models such as those discussed in Section 2-11 involve turbulent forces. Turbulence can be either favorable (average downward) or unfavorable (average upward). Favorable turbulence can maximize pest management and minimize drift.

Where the Reynolds number is > 0.1, the terminal sedimentation velocities in Table 2-7 depict rates of gravitational fall only for large droplets. Sedimentation and turbulence calculations for spray cloud transport are shown in Fig. 2-4. The wide divergence in transport calculated by sedimentation and turbulence is illustrated. Under the conditions cited sedimentation predicts that a 40 μm droplet will travel 5,000 meters downwind while turbulence indicates a downwind travel in a Gaussian envelope centering at 300 meters, not significantly different from the downwind travel of Gaussian envelopes containing droplets from 10 - 300 μm in diameter.

### 2-8.2 Estimation of Droplet Size Distribution

Numerous investigations have attempted to relate liquid characteristics, nozzle type and size, and boom pressure to the prediction of spray droplet size distribution during the atomization process. Spray ejected into still air or air in streamline flow is not identical to that developed in turbulent air stream, which has additional shear effects (Miller 1980).

The following model can be used to estimate the size and number distribution of the spray from measures of the VMD (volume median diameter) and to estimate the spray cloud size-number distribution from spray recovery data. The computations follow the description of Saucier (1981) and Miller (1980) and are based on the hypothesis that the initial number of subclouds (sc), each of which contain a small range of droplet sizes. By making use of the droplet size distribution, the range of droplet sizes contained in each sub-cloud is replaced by a single representative size, defined by the median size of the droplet in the column. The number of droplets and the volume of spray contained in the sub-cloud is held fixed during this process. The mean

volume droplet size is specified by the average diameter ($D_{sc}$)($\mu$m) and is given by:

$$\bar{D}_{sc} = 2 \left[ \frac{4}{3} \pi \int_{D_1}^{D_2} N \left[ (D)\ dD \right]^{-1} \int_{D_1}^{D_2} dV \right]^{1/3} \qquad [3]$$

where $D_1$ and $D_2$ denote the lower and upper bounds, respectively, of the droplet sizes contained in the original subcloud.

If $V_f$ represents the total volume of spray (mL) per unit distance (cm) along the flight line in droplet form and N represents the total number of droplets, then N(D), the number distribution as a function of droplet diameter is given by:

$$N(D) = V_f(D) \left[ \frac{4}{3} \pi \int_0^{\infty} \left[ \frac{D}{2} \right]^3 f(D)\ dD \right]^{-1} \qquad [4]$$

where f(D) denotes the droplet size distribution of the spray cloud.

Figure 2-6, adapted from Akesson and Yates (1974), shows observed droplet size distributions for a variety of spray types and nozzles with a logarithmic vertical drop-size scale. The near linearity of the plots illustrates the validity of log-normal distribution for modeling the size distribution. Using the log-normal assumptions, the droplet size distribution is given by:

$$f(D) = \frac{1}{\sqrt{2\pi}\ \sigma_n\ D} \exp \left[ - \frac{1}{2} \left[ \frac{\ln D - a}{\sigma_n} \right]^2 \right] \qquad [5]$$

where

$a = \ln(VMD)$ (volume median Diameter)

$\sigma_n = \ln(\sigma_o)$

$\sigma$ = standard deviation

Substituting and integrating yields the number of droplets (nsc) and the volume (Vsc) which lie in the subcloud (sc) range $D_1$ to $D_2$:

$$n_{sc} = \frac{3V}{\pi} \exp\left[ -3a - \frac{9\sigma_n^2}{2} \right] \left[ \operatorname{erf}\left[ \frac{\ln(D_2) - a}{\sigma_n \sqrt{2}} \right] - \operatorname{erf}\left[ \frac{\ln(D_1) - a}{\sigma_n \sqrt{2}} \right] \right] \quad [6]$$

$$V_{sc} = \frac{V}{2} \left[ \operatorname{erf}\left[ \frac{\ln(D_2) - (a + 3\sigma_n^2)}{\sigma_n \sqrt{2}} \right] - \operatorname{erf}\left[ \frac{\ln(D_1) - (a + 3\sigma_n^2)}{\sigma_n \sqrt{2}} \right] \right] \quad [7]$$

The mean volume droplet diameter of any sub-cloud can be computed from the following:

$$D_{sc} = 2 \left[ \frac{4\pi V_{sc}}{3n_{sc}} \right]^{1/3} \quad [8]$$

2-8.2.1 Effects of Evaporation on Droplet Size

The evaporation of water-based droplets plays an important role in determining the size of spray droplets on impaction, or the final size of

droplets in the droplet spectrum. Because of the substantial difference in rates of evaporation as a function of size, highly diluted sprays end with a skewed spray spectrum that increases spray drift.

An effective droplet size distribution can be computed based on the time to maximum deposition computed from the model and the thermodynamic relationships based on the relative humidity and droplet viscosity. The effective droplet distribution is directly related to the droplet distribution resulting from each specific nozzle configuration by partitioning the droplet into a number of discrete levels. A correction factor is applied separately to each level to derive an effective characteristic diameter for each level.

The effective droplet-size distribution by number is related to the droplet size distribution at the exit of the nozzle. Droplet size changes because of mass transport during the delivery. A serious drawback of dilute, water-based sprays is the potential for droplet size reduction by evaporation and the potential for skewing the droplet spectrum toward sizes that are not filtered out by foliage (< ~5 $\mu$m). The time rate of change of a water droplet diameter is given by the following relationship adapted from the work of Trayford and Welsh (1977):

$$d = d_o \left[ 1 - \frac{t}{t_1} \right]^{1/2} \qquad [9]$$

where

$d$ = droplet diameter ($\mu$m) at time t after release

$d_o$ = initial droplet diameter ($\mu$m)

$t$ = time after droplet release (sec.)

$t_1$ = expected lifetime of droplet (sec.)

The expected lifetime of the droplet is given by:

$$t_l = \frac{d_o^2}{\lambda w_d} \qquad [10]$$

where

$w_d$ = Wet bulb depression ( ° C)

For water droplets,

$$\lambda = 84.76 \left[ 1 + 0.24\ R_e \right]^{1/2} - 10^{-12} \qquad [11]$$

where

$R_e$ = Reynolds number of the non-evaporated droplet

The expected lifetime of the droplet ($K_d$) is given by the following equation derived by Amaden (1962):

$$t_l \approx \frac{d_o^2}{80\ \Delta T} \qquad [12]$$

where

$\Delta T$ = the difference in temperature (°C) between wet and dry bulb thermometers commonly called the wet bulb depression.

For example, at a wet bulb depression of 17°C, a 600 $\mu$m droplet has an expected lifetime of 264 sec.

2-8.2.2 Extrapolation to Non Aqueous Formulations

Evaporation of spray formulations which contain no water can be calculated considering the basic thermodynamics in the evaporation processes. The rate of evaporation is inversely related to the amount of heat which must be transferred from the surrounding air to evaporate a unit volume of spray. Therefore, differences in the amount of heat required to vaporize a unit volume of non-water spray material vis-a-vis that for water must be accounted for in computing the expected lifetime of the spray droplet based on water spray data and equations. In addition, the rate of evaporation is directly proportional to the difference between the saturation vapor pressure of the spray material, evaluated at the air temperature and the partial pressure of spray vapor already in the atmosphere.

For volatile sprays other than water, the following relationship gives the expected lifetime of a droplet:

$$\gamma_l = \left[\frac{L}{L_w}\right]\left[\frac{P_{sw} - P_{air}}{P_s}\right] \gamma_{lw} \qquad [13]$$

where

$L$ = Latent heat of evaporation of spray (J)

$L_w$ = Latent heat of evaporation for water (J)

$P_{sw}$ = Saturation vapor pressure of water at evaluated air temperature ($P_a$)

$P_{air}$ = Partial pressure of water vapor in the air

$P_s$ = Saturation vapor pressure of spray evaluated at air temperature ($P_a$)

$\gamma_w$ = Expected lifetime of a water droplet (sec)

### 2-8.3 Stokes' Law and Spray Cloud Sedimentation

Sedimentation velocities of pesticide spray droplets are usually calculated from Stokes' law (Table 2-7). Sedimentation calculations shown in Table 2-7 have no actual validity where droplets are small (<100 $\mu$m). They are usually transported on turbulent eddies, rather than by sedimentation when Reynolds numbers are < 0.1, i.e., under most field spray conditions.

The Reynolds number and the terminal velocity of a droplet in free flight are related functions. The Reynolds number for any particular droplet size is computed from knowledge of the terminal velocity of the spray droplet as:

$$R_e = \frac{e_a \, V \, D}{h} \qquad [14]$$

where

$R_e$ = Reynolds Number

$e_a$ = density of the air (mg $m^{-3}$)

V = terminal or settling velocity (m $sec^{-1}$)

D = droplet diameter ($\mu$m)

$h$ = kinematic viscosity of the air (N sec $m^{-2}$)

A droplet in free fall will accelerate downward until the gravitational force exerted on the droplet is counterbalanced by aerodynamic drag forces caused by the movement of the droplet through the viscous atmosphere. When these forces are in balance, the droplet then falls at a constant rate called the terminal or settling velocity of the droplet.

The terminal velocity is controlled by the coefficient of drag of the particles which, in general is a nonlinear function of the Reynolds number. For the particle sizes common to aerial sprays, however, it is only appropriate to operate in the lower regime of Reynolds numbers in which the coefficient of drag of spherical particles is well represented by a linear approximation. In this regime the settling velocity can be determined from Stokes' law. The settling velocity (V) given by Stokes' law is:

$$V = \frac{g\ D^2\ e_d}{18\ h} \qquad [15]$$

where

V - settling velocity (m $sec^{-1}$)

g - gravitational acceleration = 9.8 m $sec^{-2}$

D - droplet diameter ($\mu$m)

$e_d$ - specific gravity of the spray liquid (kg $m^{-3}$)

$h$ - absolute viscosity of the air (181 N sec $m^{-2}$)

The major factor determining the terminal or settling velocity of a droplet and thus its potential for turbulent transport is the droplet size. Table 2-7 presents the calculated terminal velocity for different size droplets (assuming laminar conditions and low Reynolds numbers).

In the case of liquids, the larger droplets may be deformed by aerodynamic forces that can reduce their terminal velocities below that shown.

### 2-8.3.1 Turbulent Transport

Turbulent forces are significant in transport of spray clouds whose

droplets are < 100 μm (Glotfelty and Caro, 1975). Under favorable meteorological conditions, i.e., no thermal upwelling, turbulent transport carries the spray cloud downward into the foliage canopy. The greater the turbulence, the faster the transport and the greater the probability of reaching the foliage canopy and being filtered out within that canopy. This is a factor that underlies minimization of drift as cross wind speed increases.

The effect of turbulent transport on the drift and deposition of the spray cloud can be visualized by considering a sedimenting cloud as diffusing around its center of gravity and can be related to a line source spray cloud release in the lower 15 m of the atmosphere. Initially, the spray cloud follows a linear growth pattern primarily based on dispersion. Comparisons of the results of experiments using tracer distribution and independent comparison with spray data show good agreement with the assumed linear growth law and intensity of meteorologically derived atmospheric turbulence.

Models based on classical diffusion equations tend to underestimate the speed of growth of real spray clouds. Attempts to correct this effect by superimposing a pseudo-sedimentation velocity have been attempted but have not proven to be satisfactory. Bache and Sayer (1975) provided an empirically derived scaling factor to compensate for this effect. Empirical data, by Bache (1975), indicate that an appropriate scaling term for spray deposition was related to the location of the position of the spray cloud concentration maximum near the surface. This relationship is illustrated in Equation [16]:

$$\left[\frac{\sigma}{\sigma_m}\right] = g\left[\frac{x}{x_m}\right] \qquad [16]$$

where

$\sigma$ = the standard deviation of the cloud distribution

x = downwind distance (m)

m = subscript for maximum

g = acceleration because of gravity (9.8 m $sec^{-2}$)

This result is supported by the work of Csanady (1973) and Jobson and Sayer (1970) related to the description of a diffusing cloud with sedimentary type settling. For droplets with relatively slow settling velocities, the concentration as a function of height and time is described by Equation [17], which is related to standard Gaussian dispersion considerations for an elevated line source.

$$C = \frac{Q}{\sqrt{2\pi}} * \frac{2hz}{\sigma^3} * \exp\left[ - \frac{h^2}{2\sigma^2} \right] \qquad [17]$$

where

C = concentration (droplets $ml^{-1}$ )

Q = source strength (droplet $ml^{-1}$ )

h = height of release (m)

z = height (m)

$\sigma^2$ = variance about center of cloud

$\sigma$ = standard deviation

Differentiating Equation [17] and equating the result to zero yields the following conditions for maximum concentration, $\sigma = h/\sqrt{3}$. Therefore, the maximum concentration is:

$$C_m = Q \sqrt{(2/\pi)} * \frac{z}{h^2} \left[ \frac{3}{e} \right]^{1.5} \qquad [18]$$

A knowledge of the cloud growth is a key factor in the description of airborne concentration at or near the ground level. Generalizing the exact relationship between cloud growth and airborne concentration is described by the linear relationship, $cg = b\ i\ x$. [19]

where

cg = cloud growth (m)

b = a constant of proportionality which is empirically derived

i = the turbulent intensity

x = downwind distance (m)

Therefore, the coefficient b can be written as a function of $x_m$ (the downwind distance of maximum concentration), *h* and the turbulent intensity *i* and is given by Equation [20].

$$b = \frac{h}{\sqrt{2}\ x_m\ i} \qquad [20]$$

Bean (1971) has developed an expression for turbulent intensity *i*, which is related to wind speed, w, for neutral to unstable atmospheric conditions, and where u is equal to wind speed at normalized height.

$$i = \frac{\sqrt{w^2}}{u} \qquad [21]$$

### 2-8.4 Pesticide Spray Impingement

All spray droplets have finite impingement probabilities ranging from ~0 to 1 (from ~0% to 100%). The velocity required for impingement is termed the critical impingement velocity. Large spray droplets have a critical impingement velocity ~0 and an impingement probability = 1 (100%). They impinge on peripheral foliage or fall to the ground. As droplet size decreases from the range of 100-150 μm, probability of impingement decreases i.e. becomes < 1. As the probability of impingement decreases, critical impingement velocity increases and the actual point of impingement becomes a function of the droplet size, capture cross section, velocity and turbulence and depends upon the size, geometry, and biology of the target. A significant number and mass of droplets < 100 μm penetrate through the foliage barrier and enter insect and disease vector microhabitats.

Filtration is related to foliage density. Needles in conifer foliage are efficient filters. Filtration by broad-leaf foliage has not been quantified but appears to be related to density, shape, leaf hairs, veins, roughness, cuticle wax, and edge effects.

#### 2-8.4.1 Spray Drift and Spray Efficiency/Efficacy

Spray drift is a complex scientific, social, economic, environmental, and legal problem. It involves principles of both spray physics and risk management. Based on a survey, the National Aeronautics and Space Agency reported at a NASA 1980 spray conference that aerial spray operators considered spray drift to be their most important problem. Early concepts of spray drift were reviewed by Akesson and Yates (1964). For our purposes,

spray drift is defined as those air-borne components which move downwind and outside of the defined spray area. Since almost all pesticides are volatile, primary drift consists of particulate pesticide and pesticide vapor. It can be divided into near-field (short range) and far-field (long range) drift.

Secondary drift occurs post-spray and consists of vaporization from soil and foliage plus the aerial movement of soil-pesticide particulates (Fig. 2-7). All sprays, no matter how broad their spectrum, contain a driftable component. When aqueous sprays are highly dilute, evaporation occurs rapidly with droplets smaller than 150 μm (Spillman, 1984). This skews the resultant droplet spectrum, producing a wide range of small particulates that exacerbate drift problems.

The small droplet portion of the spray cloud is delivered by turbulent eddies. Its insecticide-fungicide bioefficacy depends on ability to circumvent impingement at the foliage barrier and a concomitant ability to deliver active agent to biological targets within the foliage system. Efficacy is limited to the portion of the spray mass that reaches biological targets. Drift constitutes vapor plus those droplets that do not fall to the ground or are not filtered out by foliage. Efficacy and drift are thus inversely related dependent variables. As spray efficacy is increased, the total amount of pesticide required is decreased with a concomitant decrease in spray drift and ecosystem burden. Spray drift is a probability problem, subject to risk management principles.

In the past it was assumed that since small droplets have long calculated sedimentation times they "drift" far downwind. This is aptly illustrated in Fig. 2-5 (Akesson and Yates, 1984). Based on sedimentation calculations, droplets < 100 μm in diameter are labeled "drift-loss-indefinite

distance." The spray concepts shown in Fig. 2-5 have no analytical basis but cast a wide shadow over the pesticide use industry, acting to eliminate scientific progress in this worldwide industry.

Sedimentation is a widely used assumption in the spray efficacy literature. That literature is immense and largely without a quantitative basis. Spray spectra are usually unknown or unreported. Typically, bioassays of mortality are made, post-spray, without any knowledge of the actual sizes of droplets in the broad spectrum spray or what produced the mortality that was measured. Much of this literature which ignores underlying principles of spray physics is obsolete and a barrier to scientific progress.

The biological efficacy of pesticide sprays is determined by the efficiency of primary delivery and secondary redistribution. All spray droplets contain pesticide and, if delivered, can contribute to accumulation of a lethal dose by the target. Pesticide spray management is a really a problem in delivery probability in the use of polydisperse pesticide sprays in turbulent air streams.

The crux of pest management lies in recognition of the "window of opportunity" which is determined by probability of impingement and efficiency of delivery. Eckblad and Barry (1983) use this concept in optimization of forest sprays. When turbulence is low, droplets less than of 5 $\mu$m have a limited probability of impingement, i.e., they flow around the target. Velocity required for impingement defines the lower droplet size limit within the window of opportunity. The upper droplet size limit is determined by the efficiency of delivery. Efficiency of delivery into foliage microhabitats is size-limited to droplets < 100-150 $\mu$m. This is the upper range of efficiency for non-systemic insecticides and fungicides.

Herbicides are bioactive on any foliage, thus herbicide sprays are generally not size-limited. However, their efficiency is size-limited because mass delivery to peripheral foliage appears to peak in the range of 250 μm. As the size of droplets of herbicide sprays is increased, their efficiency falls. Droplet size and mass transport relationships in herbicide sprays have never been quantified. Droplets > 150 μm in diameter have a probability of impingement = 1 (100%), impinging on anything in their flight path. They are filtered out at the foliage-air interface or fall to the ground. Large droplets, contain most of the total mass in the spray, have a low delivery probability and a low bioefficacy. Most fall directly to the ground. Actual analytical data on droplet transport and impingement are reported in tables 2-2 to 2-5 and in Fig. 2-6.

The conifer forest can filter out spray droplets larger than ~5 μm (Crabbe et al., 1980a). They measured drift under these conditions to total < 5 % of a spray having a $D_{max}$ of 58 μm and showed that spray loss to drift ( spray droplets < 5 μm ) along with volatilized pesticide can constitute the major portion of long range drift (far field drift). Increase in turbulence enhances delivery to forest foliage and decreases losses to the ground (Joyce and Spillman, 1978). As turbulence increases, delivery efficiency and foliage impaction increases and less pesticide is lost to the ground.

The efficiency of spray application is defined in Equation [22].

$$\text{Efficiency} = \frac{\text{Effective Mass Delivery}}{\text{Total Mass Spray}} \qquad [22]$$

Factors involved in spray losses are outlined in Table 2-6.

Efficient mass delivery in pesticide sprays is that which is delivered to targets. Present spray technology centers in the use of hydraulic nozzles

in which up to 75% or more of the spray has a low bioefficacy. Replacement of the hydraulic nozzle is a significant barrier to charge because no alternative hardware has been widely accepted and no overriding pressures are acting to focus change.

Drift is also an impediment to change, e.g., the use of "still" conditions during spray application has been a "safe refuge" in the "fight against drift". Analytical data which show an increase in drift under still conditions have a basis in spray physics but no standing in current pesticide regulation.

Three factors which affect pesticide losses during spray application are estimated in Table 2-6. Reduction in delivery losses constitute the major potential for effective change in pest management.

## 2-9 PROPERTIES OF THE CANOPY ENVIRONMENT ON SPRAY INTERACTION

The properties of the canopy and the microenvironment surrounding the canopy have a large influence on pesticide deposition and behavior.

### 2-9.1 Physical Properties of Canopy

The deposition of spray within the canopy is dependent upon the structure including, leaf (needle) area and geometry, orientation, veins, edges, hairs, and stem diameter. Plant and/or tree spacing, and canopy density are also significant factors. Needles, edges, veins,and hairs maximize impingement. The smaller the droplet size, the lower the collection efficiency for any given target. The smaller the target, the greater its spray efficiency (Equation 22). The greater the crop density and roughness,

the larger the bulk removal of spray. The greater the turbulence, the greater is the foliage deposition. Far field drift is often composed of particulates < ~5 μm plus pesticide vapor. Still air increases drift (Crabbe et al., 1980a). Spray drift can be minimized as wind velocity increases (Joyce et al., 1979).

The turbulence regime within the canopy is different from that which occurs above the canopy. The collection efficiency of foliage or a crop canopy requires consideration of the probability that a droplet will hit an object (leaf or stem). Droplet collection efficiency within the canopy is directly related to the free stream air velocity, and the droplet size and inversely related to a representative foliar dimension :

$$E \propto \frac{e\ V_o\ d^2}{18\ h\ l} \qquad [23]$$

where

E = collection efficiency

$e$ = droplet density (g $cm^{-3}$)

$V_o$ = free stream air velocity (cm $sec^{-1}$)

d = droplet diameter (μm)

$h$ = air viscosity (N sec $m^{-2}$)

$l$ = representative foliar dimension

2-9.2 Micrometeorological Factors

For spray droplet sizes where gravitational sedimentation is the predominant mechanism, the vertically falling droplets could fall on horizontal surfaces of the canopy, pass directly through the canopy, or bypass

the canopy and fall to the ground. The smaller the droplet the greater is the effect of horizontal components of airflow. Therefore, a droplet falling with a sedimentation velocity ($V_s$) affected by a horizontal wind ($V_h$) will approach a horizontal surface at the angle $\alpha = \tan^{-1}(V_s/V_h)$. This indicates that the effect of sedimentation is greatest for low wind speeds.

Since the wind is generally horizontal, droplets are more disposed to impact vertical surfaces. Further, because the smaller droplets are more strongly influenced by the wind, they generally have a greater potential for inertial impact. Bache (1975) indicates that for very small droplets ($< 10$ $\mu$m) inertial impaction is the dominant factor over almost all windspeeds.

The wind velocity is rapidly attenuated within the crop canopy. At the top of the canopy, if the wind velocity is strong, the predominant deposition mechanism is by inertial impact on vertical surfaces. Down in the canopy where the wind velocity is low; the predominant deposition mechanism is sedimentation on horizontal surfaces or by turbulent transport. Figure 2-6 illustrates the influence of a forest canopy upon the windspeed profile.

The average velocity required for prediction of spray drift and delivery is a function of the local canopy and can be estimated by extension from near ground meteorologic measurements. Extension requires knowledge of the wind profile as a function of height. The wind profile within a plant canopy can be approximated by the application of exponential scaling with height:

$$u = A \exp\left[ \gamma(R - z) \right] \qquad [24]$$

where

$u$ = windspeed at normalized height (m sec$^{-1}$)

A = windspeed at the top of the canopy (m $sec^{-1}$)

R = normalized height (m)

z = height above the ground (m)

$\gamma$ = extinction coefficient whose value increases with canopy density. (ranges from about 1 to 5 for most naturally occurring vegetation canopies)

Above the canopy, the wind profile has logarithmic scaling and is approximated by:

$$u = \frac{u^*}{k} \ln(10R) \qquad [25]$$

where

u = windspeed at normalized height R > 1

$u^*$ = wind friction velocity (m $sec^{-1}$)

k = von Karman constant = 0.4

R = normalized height (m)

z = height above ground (m)

The average velocity in the profile between the ground and the application height can be found by integrating the scaling equations with respect to R, the normalized height, over the applicable limits and dividing by the normalized application height, $R_{app}$, as follows:

$$\bar{u} = \frac{\lambda}{\gamma R_{app}} (1 - \exp(-r)) + 0.435A \left[ 1.303 \left[ 1 - \frac{1}{R_{app}} \right] + \ln(R_{app}) \right] \qquad [26]$$

The potential biological effect of each spray droplet in the spray cloud

is dependent on both its transport pathways and its point of impingement. Impingement probability determines whether the spray droplet can penetrate the foliage barrier. Impingement probability also is a significant element in mathematical models being developed for computer modeling of pesticide sprays. Both validated mathematical models and the design of computer-aided spray processes will act as a guide for the recommended use of pesticide delivery systems.

The transport and impingement properties of pesticide spray droplets are predictable as a function of their size. Pesticide efficiency depends on both probability of transport to the target and probability of impingement on that target. Collection efficiency is represented in Equation [22].

### 2-9.3 Spray Delivery to Canopy

Environmental and economic considerations make it important to manage the aerial application of pesticides for maximal pest control and minimum use of resources. Zones of potential damage from pests are both contiguous to and commingled with non-target but sensitive areas. One method currently used for protecting sensitive areas is the establishment of *buffer zones*.

Pesticide spray released from aircraft or ground sprayers may, under various meteorologic conditions, drift into areas of sensitive vegetative and animal species. Pesticide applications must be carried out in an optimal manner so that minimum quantities of active ingredients will produce the maximum beneficial results. Two parameter requirements needed during both planning and operations are: (i) data that determine the pesticide drift characteristics; and (ii) data that define and/or characterize the risks attendant upon pesticide encroachment upon non-target areas.

Factors important to establishing drift characteristics include the following : (i) wind speed and direction ; (ii) droplet density and size distribution ; (iii) evaporation rate ; (iv) aircraft altitude and swath characteristics ; (v) volume and amount pesticide applied ; (vi) atmospheric conditions (turbulent or stable). The parameters required to define the risk of impact upon the environment include the following: (i) sensitive areas/species (location and type) ; (ii) pesticide toxicities/safe exposure levels ; and (iii) pesticide persistence/degradation rate.

## 2-10. CASE STUDIES ON PESTICIDE SPRAY TRANSPORT

Gas liquid chromatography (GLC or GC) for ecosystem analysis at the nanogram level was developed first by Coulson et al., (1959) followed by other chromatographic-mass spectral methods that increased detection and quantifiable sensitivity followed. These methods are widely used to study the fate of pesticides introduced into the environment.

### 2-10.1 Methods to Measure Pesticide Spray Transport

In the past half-century, artificial targets such as cards, slides, and plastic sheets have been used as tools in evaluation of spray management. Data produced through these methods are often misleading (Uk, 1977). Wiesner (1984) describes deposit cards as lacking diagnostic capabilities for interpretation of pesticide spray results and providing no insight into the reasons for success, variability or failure of spray programs.

Impingement probability studies have been limited to deposition on artificial targets. Size-limited deposition means that these deposits have no

quantitative or overall analytical significance. Further such targets are usually placed in open areas and do not even mimic deposition on adjacent foliage.

Methods for analysis of spray transport in a foliage environment were developed by Himel et al., (1965) and Himel and Moore (1967). The quantitation of spray mass transfer in foliage systems is complex as well as time and labor intensive.

Spray droplets in target and non-target areas can be determined by size and number on insects and/or natural foliage. Analytical systems which have had extensive field study include the fluorescent particle spray droplet system, (Himel et al., 1965; Himel and Moore, 1967; Himel, 1969a, 1969b); the dry liquids system, (Barry et al., 1977; Barry and Ekblad, 1978); the reversibly soluble pigment system, (Uk, 1977; Lawson and Uk, 1979); the fluorescent dye system, (Barry and Ekblad, 1978; Wiesner, 1984); the fluorescent pigment system, (Joyce, and Beaumont, 1978); and the encapsulated droplet system (Himel, 1982; Sundaram, 1982; Villaveces, 1984).

### 2-10.2 Case Studies

Case studies cited below provide critical evidence for testing the validity of the turbuuuulence theory.

#### 2-10.2.1 Scottish Forestry Service Case Study

This research compared delivery of LV (aqueous) sprays - 20 L $ha^{-1}$ and ULV (non-aqueous) sprays - 1 L $ha^{-1}$. A Micronaire nozzle was used and provided a VMD of 120-160 $\mu$m. In the 1979 tests, wind speeds of 8 to 25 km $h^{-1}$ (5-15 miles $h^{-1}$) were encountered. The high wind speeds caused operational

flying problems, but actual deposition on the trees was increased and drift was decreased. Analytical methodology included the use of fluorescent pigments and the fluorescent particle spray droplet tracer method (Joyce and Beaumont, 1978; Ruthven, 1978; Joyce et al., 1979).

2-10.2.2 Canada Case Study

Downwind transfer of fenitrothion spray was measured using tracer systems in conjunction with meteorological measurements. The VMD of the spray was 58 μm (evaporated basis). In this research, droplet deposition (by number) on balsam fir needles peaked at 10 μm. Of 5000 droplets analyzed on target needles, 90.4% (by number) were < 60 μm (Wiesner, 1984).

2-10.2.3 United States Case Study -1.

Tracer studies involved BT, carbaryl and trichlorfon sprays. More than 90% of the droplets (by number) found on needles were < 60 μm ( Barry, 1984; Barry and Ekblad, 1978; Barry et al., 1977).

2-10.2.4 Canada-USA Case Study

The encapsulated droplet tracer system is a recently developed analytical system to identify deposition patterns. The method uses spray droplets that encapsulate during transit. The capsules deposit on foliage or other surfaces as spheres or hemispheres which can be identified, measured and counted. Research groups conducting these tests included Forest Pest Management Institute (Canada), Canadian Forestry Service, U.S. Forest Service (CANUSA PROGRAM), and University of Georgia. (Villaveces, 1984)

2-10.2.5 United States Case Study -2.

The first analytical study of mass transfer by sprays using the fluorescent particle spray droplet tracer method was conducted from 1965 to 1969 (Himel and Moore, 1967, 1969b). The tests, carried out in Montana (spruce-fir forest) and Georgia (cotton field), allowed comparison of foliage and habitat differences. The $D_{max}$ was 365 $\mu$m for the forest and 800 $\mu$m for the cotton field. Spray droplets on insects killed by the sprays were analyzed. Of 101,000 droplets analyzed, 98% (by number) were < 30 $\mu$m in diameter. Delivery of spray droplets to the conifer forest insects was not different in kind from delivery to cotton insects. No spray droplets larger than 120 $\mu$m in diameter were found on insects killed by the spray.

2-10.3 Summary

Since 1965, several mass transport studies of pesticide spraying have been carried out in the United States, Canada, and Great Britain by different research groups. The data from these studies are mutually consistent even though they represent different methodologies, test protocols, and field conditions. They confirm that the delivery and impingement of pest management sprays is governed by principles of spray physics. Only spray droplets < 100 to 150 $\mu$m deliver pesticides into foliage environments; large droplets fall to peripheral foliage and the ground; and numbers of droplets, foliage density, impingement probability, and turbulence are also crucial factors. The spray application of insecticides, fungicides and herbicides involve fundamental spray management principles. Mitigation of drift is a problem in risk management because drift is a concomitant result of all spraying techniques. Drift is exacerbated by evaporation and by unfavorable application conditions.

Principles of spray physics are a basis for computer-aided spray models. It may take decades before sufficient analytical data become available for widespread acceptance of computer-aided spray models for general field use.

The analytical data collected in Tables 2-2 to 2-5 and Figure 2-4 represent major interdisciplinary research studies with sprays. Each represents application of analytical tracer systems and literally thousands of hours of field and analytical time. It is important that these data be collected, presented, and reviewed because they are a basis for change in spray technology. Change is important because the spray application of pesticides is a multibillion-pound source of pesticides in the environment. The immensity of the problem of change in this industry can be illustrated by a composite of typical observations relative to current practices: "Yes I know that large droplets cannot enter foliage, but I have to use large droplet sprays to fight drift." Analytical data are given below as Tables 2-2 to 2-5 and illustrated in Fig. 2-6. Case studies cited above also provide critical evidence for testing the validity of the turbulence theory.

## 2-11 MODELING PESTICIDE SPRAY APPLICATION

Over the last two decades, the federal government has spent considerable effort in developing computer-based spray drift models in which theoretical approaches are represented by either diffusion or ballistic models.

Diffusion models are based on the assumption that the primary mechanism which drive the motion and deposition of the aerial spray particles is the mixing and interchange resulting from the spatial variation of particle concentration. Diffusion is a one-way process in which the total particle ensemble tends toward a state of equilibrium because areas having denser

concentration with high particle interaction tend to become less dense.

Since diffusion models consider particle ensembles, they are particularly useful for describing both spray drift and the environmental impact of the spray drift. There are two principal types of diffusion models: (i) those resulting from the mathematical solution of the diffusion equation, the so-called Gaussian assumptions and (ii) those based upon finite difference of the behavior of the pesticide sprays. The latter is generally the more versatile because it permits more realism in incorporation of physical variables, for example, temperature gradients, humidity, wind, turbulence, and topography. The diffusion model is complex to operate but its benefits frequently justify the extra effort.

In the ballistic model, a spray droplet is considered as a moving spherical mass governed by Newton's laws of motion (force of gravity and air resistance). Averaging over the ensemble of particle size yields the overall time history and spatial distribution of the spray cloud. Ballistic models are used for studies of spray droplets having diameters > 100-150 $\mu$m.

Complete description of polydisperse spray clouds whose particle diameters range from hundreds down to a few micrometers requires a combination of the diffusion and ballistic modeling approaches. In these combined models the spray deposition is commonly modeled by ballistic assumptions while drift is commonly approached on the basis of diffusion analogies. Since ballistic type models are, in general, simpler to computerize, complex particle behavior, e.g. effects of aircraft vertices, droplet evaporation, changes in mass and concentration of the spray cloud and temperature gradients is most often handled by this analysis technique.

Current aerial spray models are available as follows:

### 2-11.1 FSCBG Model

The (Forestry Service, Cramer, Barry, Grim Model) is an extension of early work done for the U.S. Army's at the Dugway Proving Ground by Dumbauld et al., (1975) and carried on by the H.E. Cramer Company by Dumbauld et al., (1977). The FSCBG model is a line source model which incorporates aircraft wake settling, line source dispersion, droplet evaporation, and canopy penetration. Concentration, deposition, and dosage above and below a downwind forest canopy are calculated for multiple spray lines.

This model has been used for spray prediction in a variety of spray applications by the U. S. Forest Service, including in pine seed orchards in the southern U.S. and in spruce budworm spraying programs in Maine (Ekblad and Barry, 1984).

### 2-11.2 AGDISP Model

The AGricultural DISPersion (AGDISP) model was developed by Bilianin et al., (1981) for NASA Langley Research Center and USDA Forest Service. It is based on description of the motion of discrete droplets. Integral dynamic equations for calculating droplet trajectories are provided. The model includes the influence of the spray delivery system, wake turbulence, atmospheric turbulence, gravity, and evaporation. The model has been principally applied to large droplet sizes.

### 2-11.3 Picot Model

The Picot model for Forest Spray Dispersion and Deposition (Bask and Picot, 1984) employs a finite difference technique to solve the

diffusion-advection equation. Atmospheric turbulence, gravitational settling, droplet evaporation, atomizer type, foliage, and limited wake effects are explicitly considered.

### 2-11.4 EPAMS Model

The Environmental Prototype Automatic Meteorological System (EPAMS) model is based on the Dugway Proving Ground line source dispersion model (Dumbauld and Bjorkland, 1977). The model incorporates complex terrain wind field effects in a Gaussian instantaneous line source model. Mixing layer depths and wind velocity are estimated based on stable atmospheric assumptions. Dispersion is computed from the Gaussian assumptions. Evaporation and micrometeorological effects are ignored.

### 2-11.5 Reid and Crabbe Model

The Reid-Crabbe models (Crabbe et al., 1980abc) are finite difference gradient transfer simulation techniques that uses a Lagrangian Markov chain formulation. The models consider atmospheric turbulence, droplet evaporation, gravitational settling, and initial droplet-size spectrum.

### 2-11.6 FWG Model

The FWG (Frost and Huang, 1981) model accounts for aircraft wake parameters, spray nozzle exit parameters, and mean and statistical atmospheric properties including turbulence. A fourth-order Runge-Kutta scheme is used to solve the three differential equations of motion. An aircraft vortex wake model is currently being incorporated. Evaporation is not considered.

### 2-11.7 Bragg Model

The Bragg model (Bragg, 1981) incorporates aircraft vortex wake, droplet evaporation and propeller effects. The vortex path subroutine evaluates wing and helicopter blade surface potential flow and computes the spanwise location and strength of wing-tip vertices. Wake properties are computed based on a viscous wake model. Drift and deposition are computed from the interactions between the droplets and the wake.

### 2-11.8 Miller Model

The Miller Model (Miller, 1980) examines the dispersal of agricultural sprays from airplanes, helicopters and ground spray rigs. The model is two dimensional and neglects the micro-meteorology of the canopy and droplet evaporation. Nozzle exit size distribution functions are computed based on measured spray deposition pattern with a few simplifying assumptions concerning the distribution shape. The model is applicable to a narrow range of turbulence parameters.

### 2-11.9 Trayford and Welsh Model

The Trayford and Welsh model (1977) considers wing tip vortices, evaporation and propeller swirl and computes droplet trajectories. The model applicability is generally limited to the near field (a few wingspans from the flight line).

### 2-11.10 The Cranfield Model

The Cranfield Institute of Technology model (Bache, 1975; Bache and Sayer, 1975; Bache and Uk 1975) simulates the deposition from a cloud diffusing about its center of gravity transported with the mean wind. The model was originally developed for the evaluation of agricultural spraying and neglects canopy factors and droplet evaporation. When combined with the canopy models also developed at the Cranfield Institute of Technology, realistic estimates of droplet transport within canopies are developed.

### 2-11.11 Loats/AIPHS Model

This model developed by Loats Associates, Inc. is an extension of the Cranfield model (Loats and Lloyd, 1983). The model was developed to simulate the dispersion and deposition of insecticides and herbicides to agricultural crops. The model includes methods for accounting for the effects of droplet evaporation. It is available in several forms including versions that run on small handheld calculators.

## 2-12 RESEARCH NEEDS FOR IMPROVED SPRAY TECHNOLOGY

Well-engineered, efficient pesticide delivery systems are urgently needed. The spray application of pesticides has never developed beyond its empirical basis. Most of the spray methods used today are deeply entrenched and difficult to change. If change is to come to pesticide spray methods, it must be based on widely available analytical mass transfer data. Because all methods for analyzing the mass transfer are time and labor intensive, there is a need for automation of foliage deposit analysis to make wide ranging data available to field agriculturists. Analysis of foliage samples must be adapted

to digital video methods. Wide availability of automated methods and their data is a key step to implement new methodologies in spray transfer and pest management.

There is a critical need to test and evaluate existing or improved mathematical models so that computer directed field spray programs can be developed and made readily available. The available models need extensive field testing in conjunction with analytical systems to justify widespread adaptation to computer programs aimed at pesticide efficiency, optimized pest management and risk management of drift.

## 2-13 CONCLUSIONS

From the above discussion on spray physics we conclude that:

1. Delivery efficiency for pesticide sprays is size-limited. The ultimate question is whether investment in large droplets in sprays is economically sound and biologically relevant in treating foliage systems.

2. Present spray technology does not conform to underlying principles of spray physics, thus it needs to undergo major change in methods and hardware. That change will, however, be slow because present methods appear to be rational and are deeply rooted. Principles of spray physics are a valid basis for computerized spray models.

3. Most current pesticide spray methods are inefficient. New, delivery technology must be based on efficient delivery to the target.

4. Broad-spectrum, polydisperse pesticide sprays can be evaluated by division into two discrete size segments > 150 $\mu$m having a probabilities of impingement = 1. Sizes < 100-150 $\mu$m have an impingement probability < 1. This is a major factor in determining the bioefficacy of sprays.

5. A foliage barrier exists for spray droplets > 100-150 μm. They are filtered out in the first few millimeters of foliage.

6. Most insects and disease vectors live within a protective microhabitat. Effective management requires delivery of the pest control agent into and on that microhabitat.

7. Mass and droplet transfer in herbicide sprays has never been quantified.

8. Spray drift is the overriding factor in the use of herbicides. Control of spray drift using ultra-large, polydisperse sprays is not an ultimate solution.

9. Most pesticides are subject to volatilization from sprays, from foliage and from the ground. This is an environmental management problem whose significance has not been properly evaluated.

10. Efficient pesticide delivery systems must be developed.

## REFERENCES


Akesson, N.B., and W.E. Yates. 1964. Problems relating to application of agricultural chemicals and resulting drift residues. Ann. Rev. Entomol. 9:285-318.

Akesson, N.B., and W.E. Yates. 1974. The use of aircraft in agriculture. FAO Agricultural Development Paper No.9, FAO, Rome.

Akesson, N.B., and W.E. Yates. 1984. Physical parameters affecting aircraft spray application. p. 95-115. *In* W. Y. Garner and J. Harvey, Jr. (ed.) Chemical and biological controls in forestry. ACS Symposium Series 238, Am. Chem. Soc., Washington DC.

Amaden, R.C. 1962. Reducing the evaporation of sprays. Agric. Aviat. 4:88-93.

Bache, D.H. 1975. Transport of aerial spray. III. Influence of microclimate on crop spraying. Agric. Meteorol. 15:379-383.

Bache, D.H. 1985. Prediction and analysis of spray penetration into plant canopies. Brit. Crop Prot. Counc. Monogr. 28:183-190.

Bache, D.H., and W.J.D. Sayer. 1975. Transport of aerial spray, I. A model of aerial dispersion. Agric. Meteorol. 15:257-271.

Bache, D.H., and S. Uk. 1975. Transport of aerial spray, II. Transport within a crop canopy. Agric. Meteorol. 15:371-377.

Bache, D.H., and M.H. Unsworth. 1977. Some aerodynamic features of a cotton canopy. J. Royal. Meteorol. Soc. 103:121-134.

Bailey, G.W., L.A. Mulkey, and R.R. Swank, Jr. 1985. Environmental implications of conservation tillage: A systems approach. p. 240-265. *In* F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publ, Chelsea, MI.

Bailey, G.W., R.R. Swank, Jr., and H.P. Nicholson. 1974. Predicting pesticide runoff from agricultural land: A conceptual model. J. Environ. Qual. 3:95-102.

Barry, J.W. 1984. Deposition of chemical and biological agents in conifers. p. 117-137. *In* W.Y. Garner and J. Harvey, Jr. (ed.) Chemical and biological controls in forestry. ACS Symp. Ser. 238. Am. Chem. Soc., Washington DC.

Barry, J.W., W.M. Ciesla, M. Tysowsky, Jr., and R. B. Ekblad. 1977. Impaction of insecticide particles on western spruce budworm larvae and douglas-fir needles. J. Econ. Entomol. 70:387.

Barry, J.W., and R.B. Ekblad. 1978. Deposition of insecticide drops on coniferous foliage. Trans. ASAE. 21:438-441.

Basak, N. and J.C.C. Picot. 1984. Langrangian simulator of forest pesticide spray dispersion and deposition. p 373-398 *In* P.W. Volsey (ed.) Proc. Symp. Agricultural and Forestry Aviation. National Research Council, Ottawa, Canada.

Beyerlein, D.C., and A.S. Donigian Jr., 1979. Effectiveness of soil and water conservation practices for pollution control. p. 385-473. *In* USEPA, EPA-600/3-74-106. U.S. Government Printing Office, Washington, DC.

Bean, G.A. 1971. The variations of the statistics of wind temperature and humidity. Fluctuations with stability. Boundary-Layer Meteorol. 1:438-457.

Bilanin, A.J., M.E. Teske, and D.J. Morris. 1981. Predicting aerially applied particle deposition by computer. Soc. of Automotive Eng. Kansas City, KS.

Bragg, M.B. 1981. A numerical simulation of the dispersal of aerial sprays. NASA Contractor Rep. 165816. Ohio State Univ., Columbus, OH.

Brown, A.W.A. 1951. Insect control by chemicals. John Wiley and Sons, New York.

Carsel, R.F., and C.N. Smith. 1987. Impact of pesticides on ground water contamination. p. 71-83. *In* G.J. Marco et al. (ed.) Silent Spring Revisited. Am. Chem. Soc., Washington DC.

Computer Sciences Corporation. 1980. Pesticide runoff simulator (PRS) user's manual. Prepared for the Office of Pesticides and Toxics. USEPA, Washington, DC.

Coulson, D.M., L.D. Cavanagh, and J. Stuart. 1959. Gas chromatography of pesticides, J. Agric. Food Chem. 7:250-251.

Crabbe, R., L. Elias, M. Krzymien, and S. Davie. 1988. New Brunswick forestry spray operations: Field study of the effect of atmospheric stability on long range pesticide drift. Nat. Aeronaut. Estab. LTR-UA-52. Nat. Res. Counc. of Canada, Ottawa, ON.

Crabbe, R., L. Elias, M. Krzymien, and S. Davie. 1980b. Field study of effect of tmospheric stability on target deposition and effective swath widths for aerial forest sprays in New Brunswick. Nat. Aeronaut. Estab. LTR-UA-61. Nat. Res. Counc. of Canada, Ottawa, ON.

Crabbe, R., M. Kzymien, L. Elias, and S. Davie. 1980c. New Brunswick forestry spray operations: Measurement of atmospheric fenitrothion concentrations near the spray area. Nat. Aeronaut. Estab. LTR-UA-56. Nat. Res. Counc. of Canada, Ottawa, ON.

Cramer, H.E., and G. Boyle. 1976. The meteorology and physics of spray particle behavior. Pesticide spray application and assessment: Workshop proceedings. USDA Forest Serv. Rep. PSW 16. U.S. Government Printing Office, Washington, DC.

Csanady, G.T. 1973. Turbulent diffusion in the environment. Reidel Publ., Boston.

Donnigan, A.S., Jr., and N.H. Crawford, 1976. Modeling pesticides and nutrients on agricultural land. USEPA, EPA 600/12-76-043. U.S. Government Printing Office, Washington, DC.

Dumbauld, R.K., and J.R. Bjorklund. 1977. Mixing-layer analysis routine and transport/diffusion application routine for EPAMS. Atmospheric Sciences Lab., U. S. Army Electronics Command, White Sands Missile Range, New Mexico, AD AO38399, U.S. Government Printing Office, Washington, DC.

Dumbauld, R.K., H.E. Cramer, and J.W. Barry. 1975. Application of meteorological prediction models to forest spray problems. Rep. TECOM 5-CO-403-000-051, DPG Doc.DPG-TR-M935P. U.S. Army Dugway Proving Ground, U.S. Government Printing Office, Washington, DC.

Ebeling, W. 1963. Analysis of the basic processes involved in the deposition, degradation, persistence and effectiveness of pesticides. Residue Rev.

33:35-163.

Ekblad, R.B., and J.W. Barry. 1983. A review of progress in technology of aerial application of pesticides. USDA Forest Serv. 3400-Forest Pest Management 83342808. U.S. Government Printing Office, Washington, DC.

Ekblad, R.B., and J.W. Barry. 1984. Technical progress in aerial application of pesticides. p. 79-94. *In* W. Y. Garner and J. Harvery, Jr. (ed.) Chemical and biological controls in forestry. ACS Symp. Ser. 238. Am. Chem. Soc., Washington DC.

Gohlich, H. 1983. Formation of drift and basic considerations for its reduction. p. 271-288. *In* R. Greenhalgh and N. Drescher (ed). Pesticide Chemistry: Human welfare and the environment. Permagon Press, New York.

Frost, W. and K.H. Huang. 1981. Monte Carlo model for aircraft applications of pesticides. ASAE Paper 81-1507. Chicago, Illinois.

Glotfelty D.E, and J.H. Caro. 1976. Pesticide volatilization. *In* V.R. Dietz (ed.) Removal of trace contaminates from the air. ACS Symp. Ser. 17, ACS, Washington DC.

Greenhalgh, R. 1986. Definition of persistence in pesticide chemistry. Pure Appl. Chem. 52:2565-2566.

Grover, R., J. Maybank, K. Yosida. 1972. Droplet and vapor from butylester and dimethylamine salt of 2,4-D. Weed Sci. 20(4):320-324.

Himel, C.M. 1969a. The fluorescent particle spray droplet tracer method. J. Econ. Entomol. 62:912-916.

Himel, C.M. 1969b. The optimum size for insecticide spray droplets. J. Econ. Entomol. 62:919-925

Himel, C.M. 1974. Analytical methodology in ULV. Brit. Crop Prot. Counc. Monogr. 11:113-119.

Himel, C.M. 1982. Analytical systems for pesticide spray transport and impingement. ASAE Paper 82-1001.

Himel, C.M., and A.D. Moore. 1967. Spruce budworm mortality as a function of aerial spray droplet size. Science. 156:1250-1251.

Himel, C.M., L. Vaughn, R.P. Miskus, and A.D. Moore. 1965. A new method for spray deposit assessment. U.S. Forest Service Pacific Southwest Forest and Range Exp. St. PSW-87. U.S. Government Printing Office, Washington, DC.

Jobson, H.E., and W.W. Sayer. 1970. Predicting concentration profiles in open channel flows. Proc. ASCE J. Hydraul. Div. 96:1983-1996.

Joyce, R.J.V., and J. Beaumont. 1978. Collection of spray droplets and chemical by larvae, foliage and ground deposition. p. 63-80. *In* A.V. Holden and D. Bevan (ed.) Control of the pine beauty moth by fenitrothion in Scotland. Forestry Commission, Scotland.

Joyce, R.J.V., G.W. Schaefer, and K. Allsopp. 1979. Distribution of spray and assessments of larval mortality at Annabaglish. p. 15-46. *In* A.V. Holden and D. Bevan (ed.) Aerial application of insecticide against pine beauty moth. Forestry Commission, Scotland.

Joyce, R.J.V., and J.J. Spillman. 1978. Discussion of aerial spraying techniques. p. 13-24. *In* A.V. Holden and D. Bevan (ed.) Control of the pine beauty moth by fenitrothion in Scotland. Forestry Commission, Scotland.

Kearney, P.C., and D.D. Kaufman. 1975. Herbicides: Chemistry, degradation and mode of action. Marcel Dekker, New York. Vol. I.

Kearney, P.C., and D.D. Kaufman. 1976. Herbicides: Chemistry, degradation and mode of action. Marcel Dekker, New York. Vol. II.

Keathley, J.P. 1972. Distribution of insecticide spray and efficiency in application. Ph.D. diss. Univ. of Georgia, Athens. (Diss. Abstr. 73-5722).

Klingman, G.C., and F.M. Ashton. 1982. Weed science: Principles and practices. 2nd. Ed. John Wiley and Sons, New York.

Kubr, R.J., and H.W. Poogh. 1976. Carbamate insecticides: Chemistry, biochemistry and toxicology. CRC Press, Cleveland.

Lawson, T.J., and S. Uk. 1979. The influence of wind turbulence, crop characteristics and flying height on the dispersal of aerial sprays. Atmos. Environ. 13:711-715.

Leonard, R.A., G.W. Bailey, and R.R. Swank, Jr. 1976. Transport, detoxification, fate, and effects of pesticides in soil and water environments. p 48-78. *In* Land application of waste materials. Soil Consv. Soc. Amer. Ankeny, IA.

Linscott, D.L., and R.D. Hagin. 1968. Interaction of EPTC and DNBP on seedlings of alfalfa and birdsfoot trefoil. Weed Sci. 16(2):182-184.

Loats, H.L., and D.G. Lloyd. 1983. Final report for "pesticide aerial drift/risk management model development." Contr. 53-3294-1-24. USDA-APHIS, Hyattsvile, MD.

Lofgren, C.S., D.W. Anthony, and G.A. Mount. 1973. Size of aerosol droplets impinging on mosquitoes as determined with a scanning electron microscope. J. Econ. Entomol. 66:1085-1088.

Luken, R.J. 1971. Chemistry of fungicidal action. Springer-Verlag. New York.

Marsh, R.W. (ed.). 1972. Systemic fungicides. Longman, London.

McGuffog, D.R., N. Plowman, and T.P. Anderson. 1984. Controlled release formulation of chlorpyrifos in thermoplastic granule matrix. p. 429-436. *In* Proc. Brit. Crop Protection Conf. -- pests and diseases, Brigton, England, 19-22 Nov. Brit. Crop Prot. Counc. Croydon, England.

Medved, L.I. 1975. Circulation of pesticides in the biosphere. p. 119-128. *In* P. Varo (ed.) Pesticide chemistry vol.3. (Helsinki-1974). Butterworth, London.

Metcalf, R.L. 1955. Organic insecticides: Their chemistry and mode of action. Interscience Publ, New York.

Miller, C.O. 1980. A mathematical model of aerial deposition of pesticides from aircraft. Environ. Sci. Tech. 14(7):824-831.

Reid, J.D., and R.S. Crabbe. 1980. Two models for the long-range drift of

forest pesticide aerial spray. Atmos. Environ. 14:1017-1025.

Ripley, B.D., and L.V. Edington. 1983. Internal and external plant residues and relationships to activity of pesticides. p. 545-553. *In* Proc. of the 10th Int. Congr. Plant Protection for Human welfare, Brigton, England. 20-25 Nov. Brit. Crop Prot. Counc., Croydon, England.

Ruthven, A.D. 1978. Deposition of fenitrothion at ground level. p. 95-102. *In* A. V. Holden and D. Bevan (ed.) Control of pine beauty moth by fenitrothion in Scotland. Forestry Commission, Scotland.

Saucier, R. 1981. A mathematical model for the vapor and mass distribution from a falling evaporating aerosol cloud. U. S. Army Armament Res. and Development Command, Chemical Systems Lab., Aberdeen Proving Ground. ARCSL-TR-81007. U.S. Government Printing Office, Washington, DC.

Sayer, H.J. 1959. An ultra-low-volume spraying technique for the control of the desert locust. Bull. Entomol. Res. 50:371-386.

Sharville, E.G. 1979. Plant disease control. AVI Publ. Co., Westport, CT.

Sirons, G.J., G.W. Anderson, R. Frank and B.D. Ripley. 1982. Persistence of hormone-type herbicide residue in tissue of susceptible crop plants. Weed Sci. 30:572-578.

Smith, C.N., G.W. Bailey, R.A. Leonard, and G.W. Langdale. 1978. Transport of agricultural chemicals from small upland peidmont watersheds. USEPA EPA-600/3-78-056. U.S. Government Pringting Office, Washington, DC.

Smith, C.N., and R.F. Carsel. 1984. Foliar washoff of pesticides (FWOP) model: Development and evaluation. J. Environ. Sci. Health. B19:323-342.

Smith, C.H., W.P. Payne Jr., L.A. Mulkey, J.E. Benner, R.S. Parrish and M.C. Smith. 1981. The persistence and disappearance by washoff and dry fall of methoxychlor from soybean foliage: A preliminary study. J. Environ. Sci. Health. B16:774-794.

Spillman, J.J. 1984. Evaporation from freely falling droplets. The Aeronautical J. Royal Aero. Soc. 42:181-185.

Spillman, J.J. and R.J.V. Joyce. 1978. Low-volume and ultra-low-volume spray

trials from aircraft over Thetford Forest in control of pine beauty moth by fenitrothion in Scotland. p. 31-51. In A.V. Holden and D. Bevan (ed.), Control of the pine beauty moth by fenitrothion in Scotland. Forestry Commission, Scotland.

Sundaram, A. 1982. Foliar impaction and distribution of aerially sprayed encapsulated droplets. ASAE Paper 82-1006., St. Joseph, MI.

Torgeson, D.C. (ed). 1969. Fungicides. Chemistry and physiology. Vol.2. Academic Press, New York.

Trayford, R.S., and L.W. Welch. 1977. Aerial spraying: A simulation of factors influencing the distribution and recovery of liquid droplets. J. Agric. Eng. Res. 22:183-196.

Uk, S. 1977. Tracing insecticide spray droplets by sizes on natural surfaces. The state of the art and its value. Pestic. Sci. 8:501-509.

U.S. Department of Agriculture, Science and Education Administration. 1980. CREAMS, A field scale model for chemicals runoff and erosion for agricultural management systems. *In* W.G. Kniesel (ed.) Conserv. Res. Rep. 26. USDA-SEA, Washington, DC.

U.S. Environmental Protection Agency. 1979. National household pesticide usage study, 1976-1977. USEPA EPA 540/9-80-002.126. U.S. Goverment Printing Office, Washington, DC.

Van Valkenburg, J.W. 1973. The stability of emulsions. p. 93-112. *In* J.W. Van Valkenburg (ed.) Pesticide formulations. Marcel Dekker, New York.

Villaveces, A. 1984. Spray droplet transfer in forest pest management. M. S. thesis. Department of Entomology, Univ. of Georgia, Athens, GA.

Weed Science Society of America. 1983. Herbicide handbook. 5th Ed. Weed Science Society of America, Champaign, IL.

Wiesner, C.J. 1984. Droplet deposition and drift in forest spraying. p. 140-147. *In* W. Y. Garner and J. Harvey, Jr. (ed.) Chemical and biological control in forestry. ACS Symp. Ser. 238, Amer. Chem. Soc., Washington, DC.

Willis, G.H., L.L. McDowell, L.D. Meyer, and L.M. Southwick. 1982. Toxaphene washoff from cotton plants by simulated rainfall. Trans. ASAE 25:642-646.

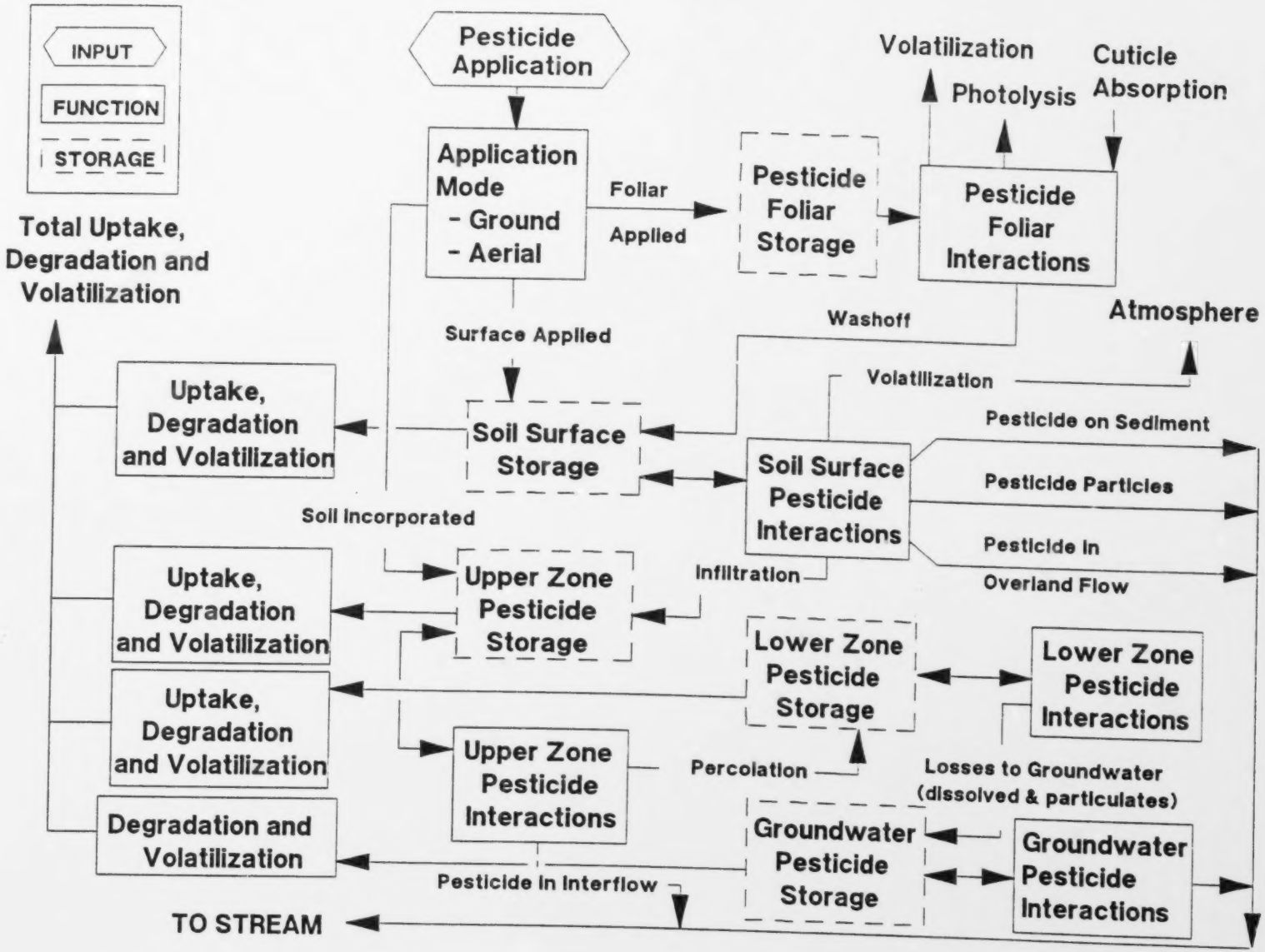


Figure 2-1. Pesticide transport and transformation in the soil-plant environment and vadose zone (After Donigian and Crawford, 1976).

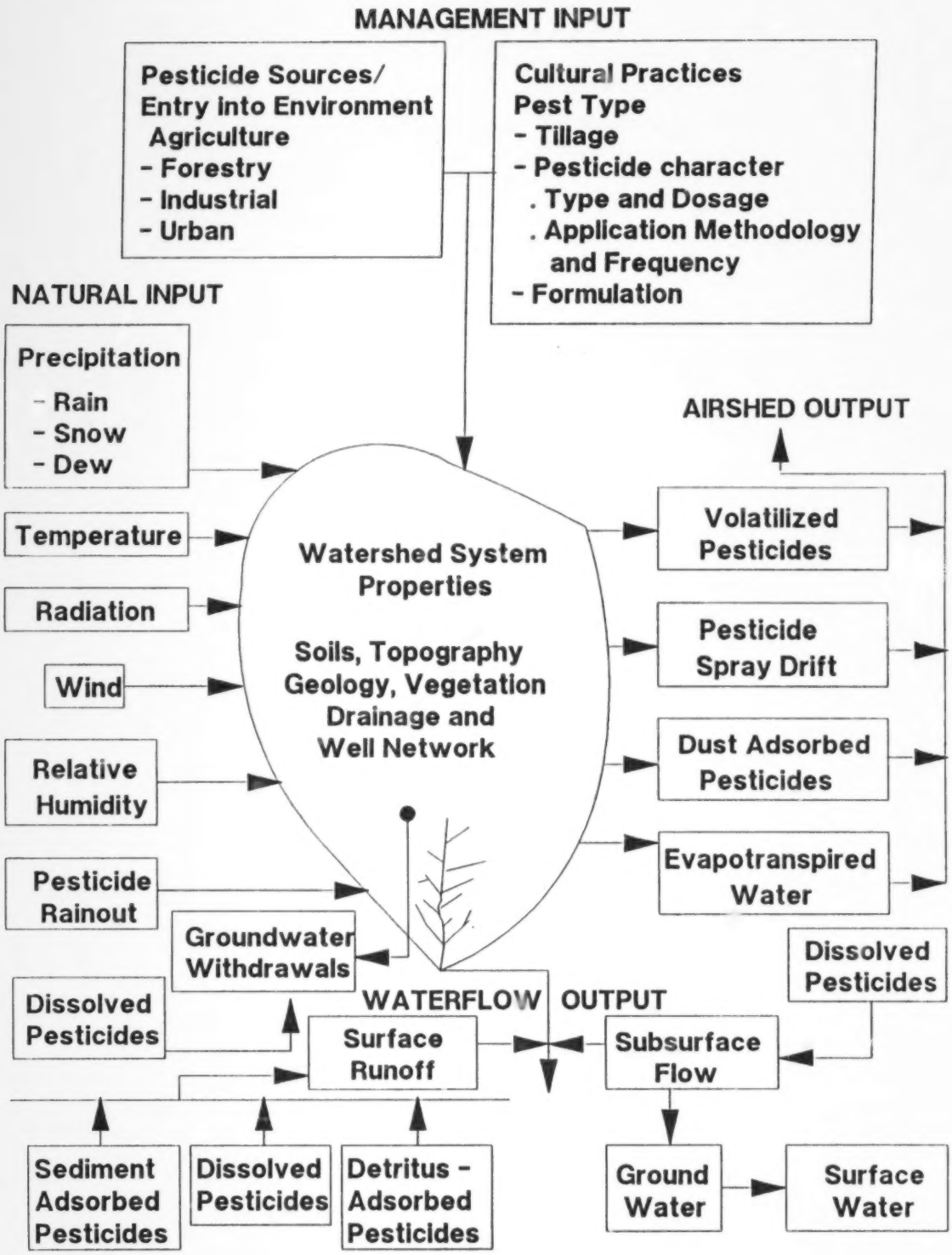


Figure 2-2. Factors influencing the behaviour and export of pesticides from a watershed (After Bailey et al., 1985).

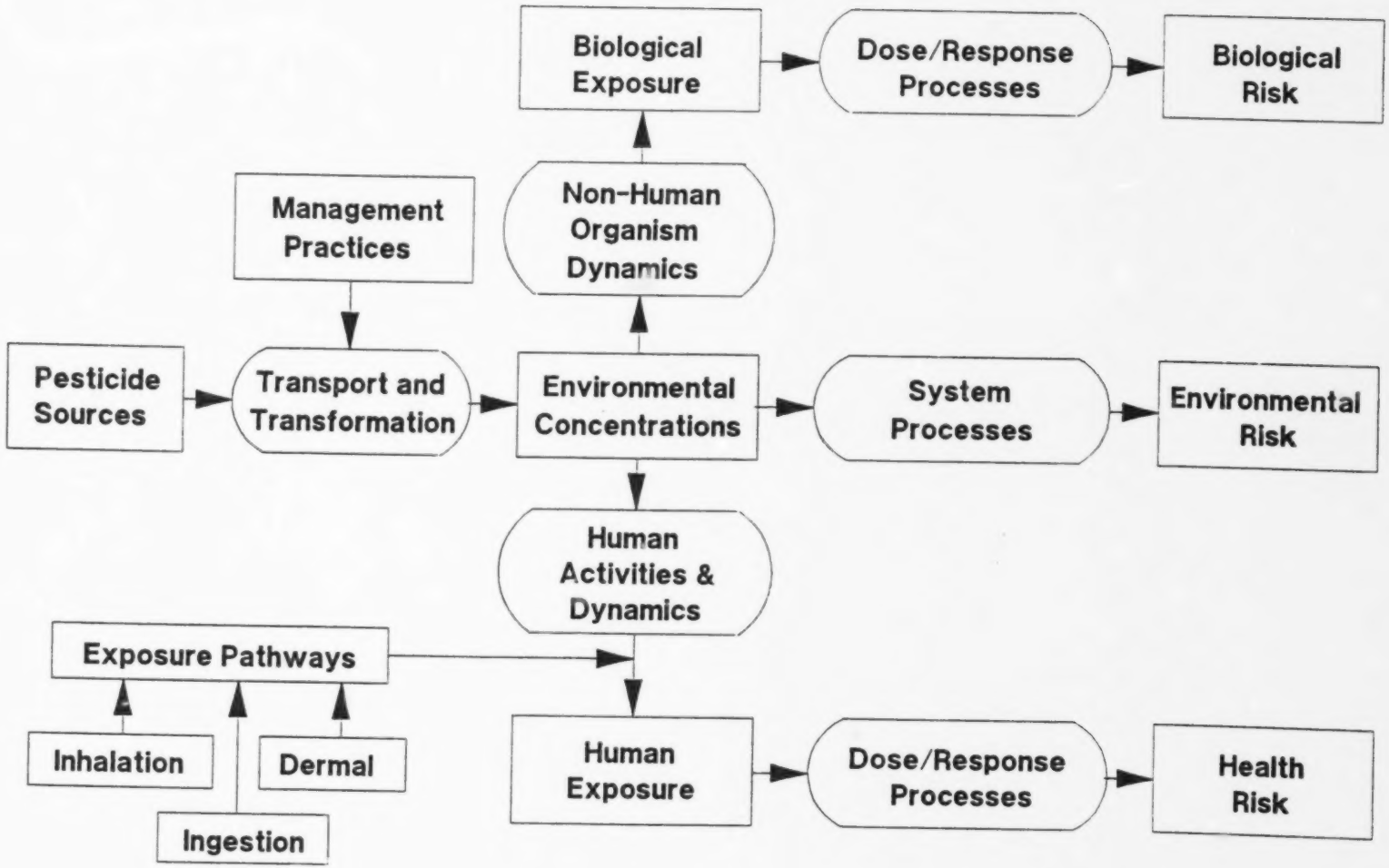


Figure 2-3. Concept of pesticide exposure and risk assessment.

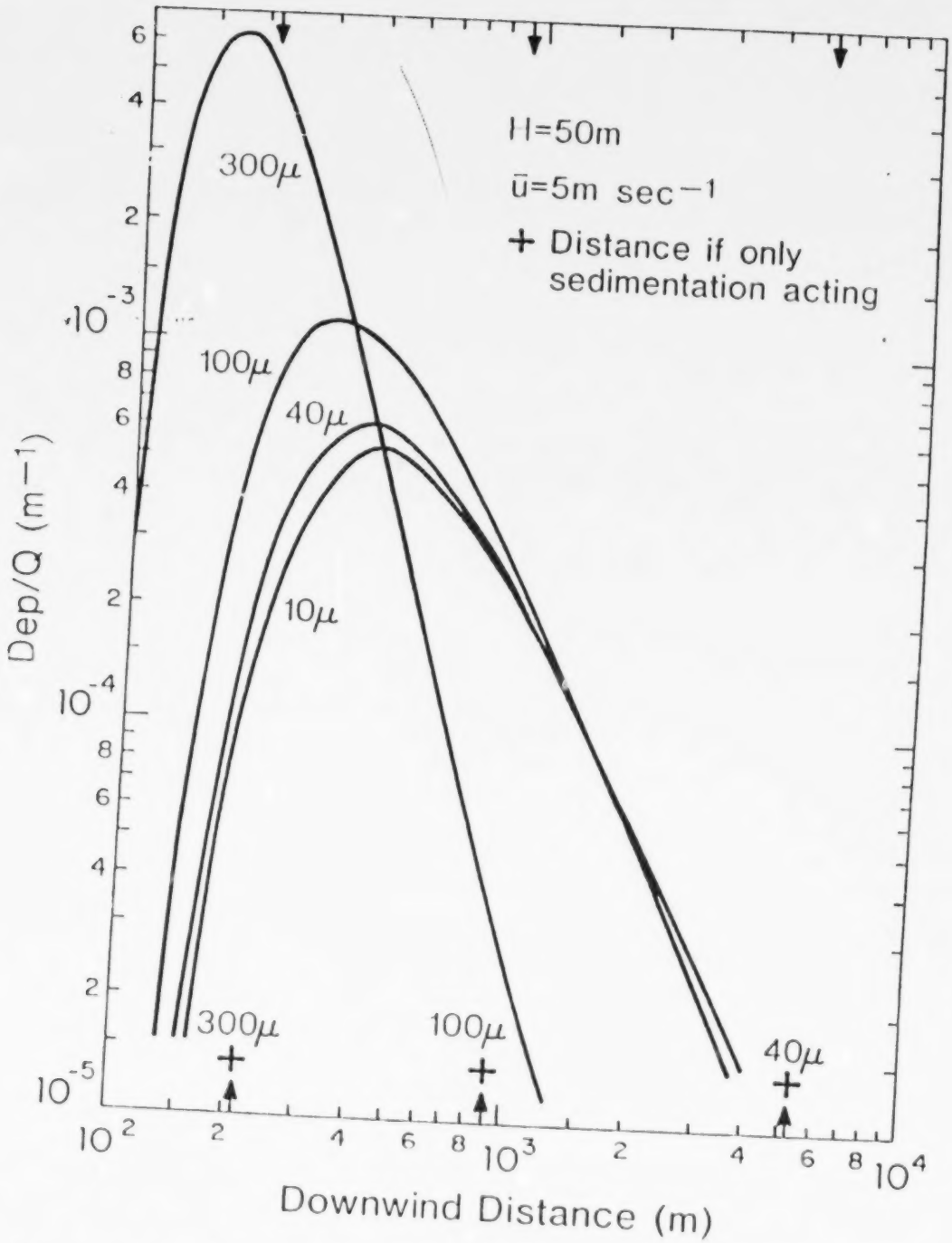


Figure 2-4. Calculated transport of pesticide spray (After Cramer and Boyle, 1976).

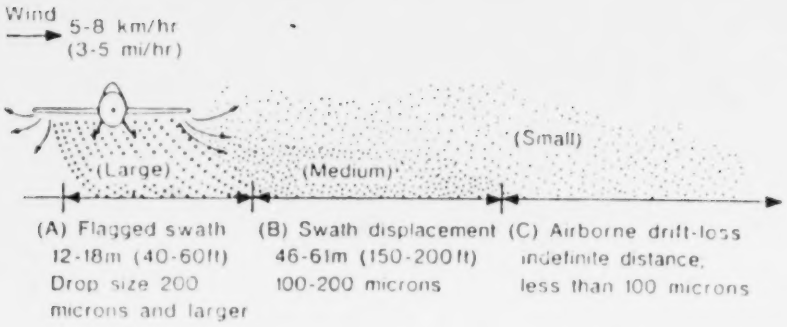


Figure 2-5. Drift calculated by sedimentation theory. Reproduced from Akesson and Yates, 1984. Reprinted with permission from ACS Symposium Series, 238, Copyright, 1984.

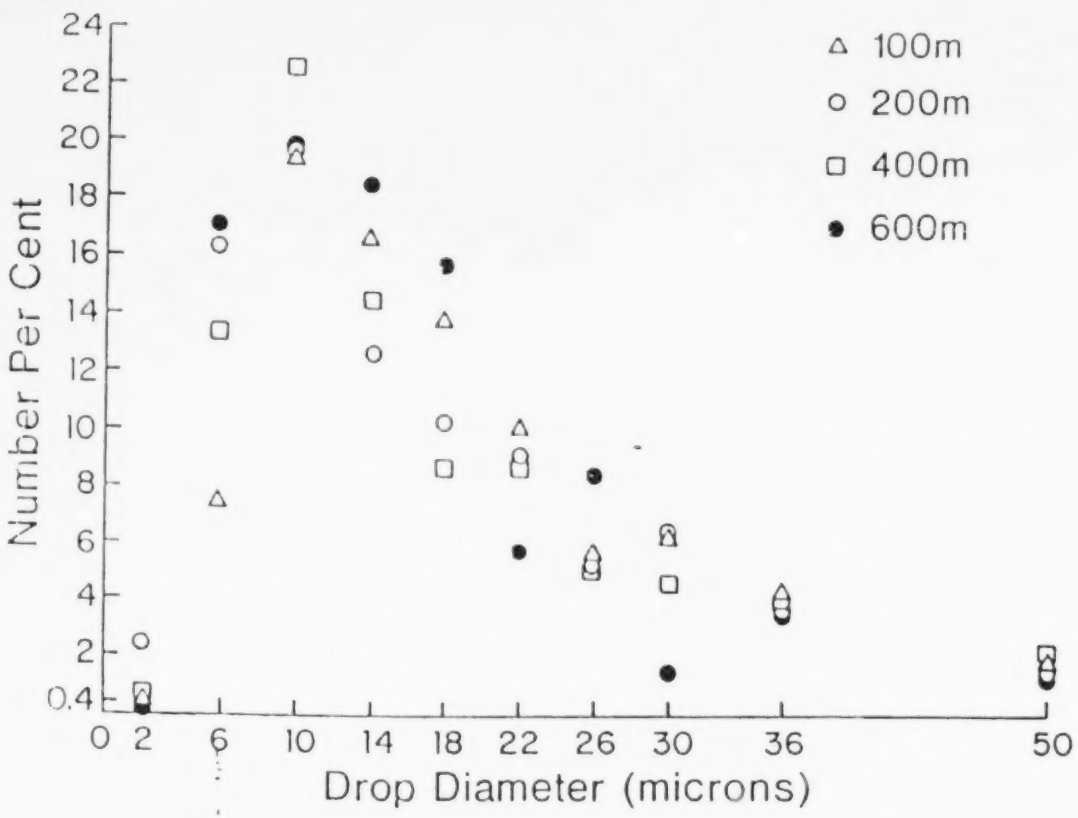


Figure 2-6. Droplet spectra deposited on balsam fir needles under unstable conditions - 100, 200, 400 and 600 meters from the swath. Reproduced from Wiesner, 1984. Reprinted with permission from ACS Symposium Series, 238, Copyright, 1984.

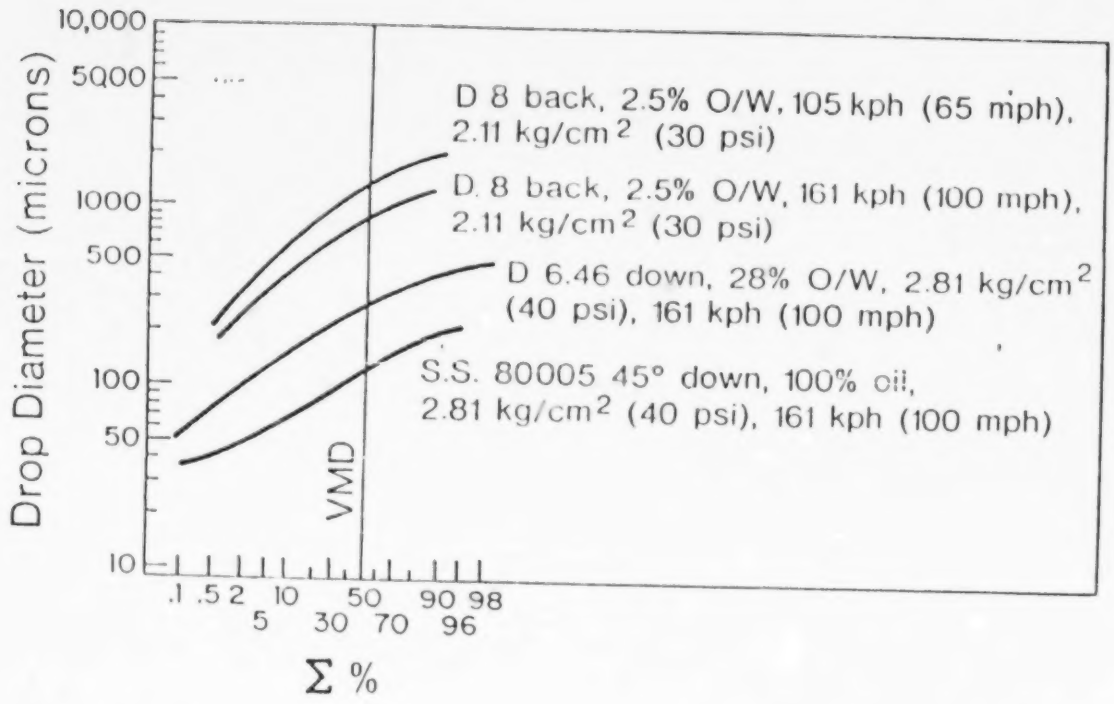


Figure 2-7. Log normal distribution of drop diameters.

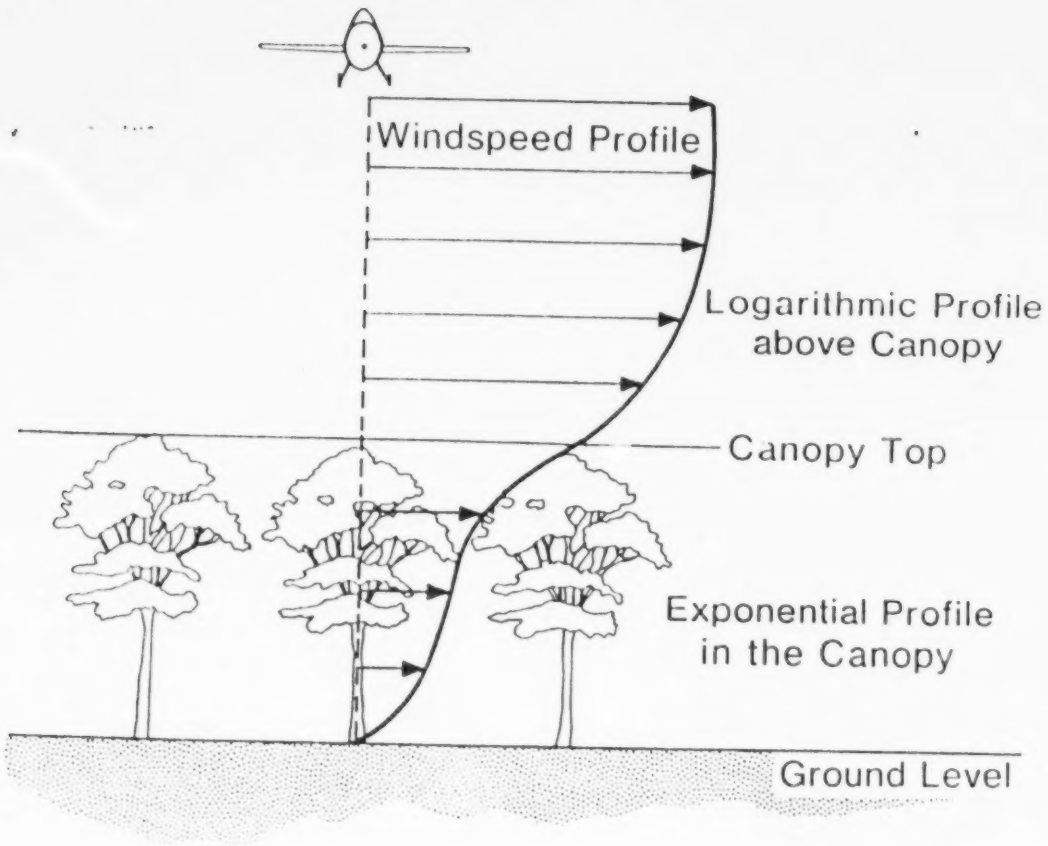


Figure 2-8. Forest canopy influence on windspeed profile.

Table 2-1 **Pesticide Sources and Environmental Exposure Pathways.**

| Pesticide Source | Transport Process | Exposure Pathway | Receptor (Population at risk) |
|---|---|---|---|
| canopy | volatilization | inhalation skin contact | human animals |
| crop residue | volatilization | inhalation/ skin contact | human animals |
| soil surface | volatilization | inhalation/ skin contact | human animals |
| root zone and below | volatilization | inhalation/ skin contact | human animals |
| grain/foilage | manufacturing /feeding* | food/ingestion | human animals |
| crop residue | overland flow* | surface water (potable water)/ ingestion | human fish |
| runnoff | overland flow* | surface water (potable water and food chain) | human fish |
| eroded soil particles and formulation - bound | overland flow* | ingestion surface water (food chain)/ ingestion, contact | fish |
| leachate -dissolved -bound on colloidal particles | leaching/ percolation* | groundwater (potable water)/ ingestion | human animals |

* Environmental flux of concern to either on-site or off-site receptors. After Bailey et al., 1985.

Table 2-2 **Comparison of LV and ULV sprays in Pine Beauty Moth Control in Scotland, 1978.**

| | LV* | ULV |
|---|---|---|
| mean deposit (μg/20 needles) | 23.6 | 41.2 |
| mean deposit (μg/single bud) | 17.5 | 18.8 |
| mean deposit (μg/larvae) | 4.4 | 22.4 |
| lost outside target area (%) | 20 | 1 |
| lost to ground (%) | 38 | 5 |
| collected by target surfaces (%) | 42 | 94 |
| average size of droplet on needles | 50 μm | 50 μm |
| maximum size droplet on needles | ~120 μm | ~120 μm |
| 90 % of droplets found on ground | >150 μm | >150 μm |

* Both LV and ULV sprays were produced by a Micronaire nozzle under conditions to optimize the spray spectra available from the nozzle (VMP 120 - 160 μm). Pigment and the fluoresent particle spray droplet tracer methods were used (After Joyce and Beaumont, 1978; Ruthven, 1978; and Joyce et al., 1979.).

Table 2-3 **Number of Droplets Observed on Conifer Needles by Size Categories in a U.S. Forest Service Field Trial, 1975 with Three Different Pesticides*.**

| Drop Size range (μm) | Pesticide Type: Bt[1] # | Bt cum.% | Carbaryl # | Carbaryl cum.% | Trichlorfon # | Trichlorfon cum.% |
|---|---|---|---|---|---|---|
| < 4 | 108 | 16 | 137 | 11 | 353 | 19 |
| 4-10 | 239 | 51 | 236 | 31 | 323 | 36 |
| 10-15 | 139 | 71 | 106 | 40 | 200 | 47 |
| 15-21 | 28 | 75 | 139 | 51 | 228 | 59 |
| 21-31 | 90 | 89 | 254 | 73 | 338 | 77 |
| 31-41 | 10 | 90 | 76 | 79 | 116 | 83 |
| 41-61 | 24 | 94 | 88 | 86 | 57 | 86 |
| 61-81 | 25 | 97 | 73 | 92 | 108 | 92 |
| 81-121 | 7 | 98 | 45 | 96 | 87 | 97 |
| 121-151 | 8 | 99 | 26 | 98 | 21 | 98 |
| 151-200 | 1 | 99 | 17 | 99 | 24 | 99 |
| > 200 | 2 | 100 | 5 | 100 | 18 | 100 |

* (After Barry, 1984; Barry and Ekblad, 1978; Barry et al., 1978)

1. Bacillus thuringiensis

Table 2-4 **Encapsulated Droplets on Conifer Needles in a Canadian - U.S. Field Trial, 1982 - 1983*.**

| Drop size μm | Average Size, μm | Number % | Cum. % | Volume % | Cum.% |
|---|---|---|---|---|---|
| 2-5 | 3 | 3 | 3 | 0 | 0.0 |
| 6-10 | 8 | 14 | 17 | 0.3 | 0.3 |
| 11-20 | 15 | 47 | 64 | 7.8 | 8.14 |
| 21-30 | 25 | 24 | 88 | 24 | 31.6 |
| 31-40 | 35 | 8 | 96 | 24.5 | 56.1 |
| 41-50 | 45 | 2.3 | 98 | 13.8 | 70 |
| 51-75 | 63 | 0.9 | 99 | 9 | 79 |
| 76-100 | 88 | 0.7 | 99.8 | 15.5 | 94 |
| 101-125 | 100 | 0.1 | 100 | 5.9 | 100 |

* (after Crabbe et al., 1980 a, b, c.)

Table 2-5 **Insecticide Spray Droplet Distribution on Four Insects from Five Different Field Studies*.**

| | Droplet Size Range (μm) | | | | | |
|---|---|---|---|---|---|---|
| | 21-30 | 31-40 | 41-50 | 51-60 | 61-120 | >120 |
| | Droplet Percent | | | | | |
| Spruce budworm[1] | 92 | 3.5 | 1.7 | 1.4 | --- | --- |
| Boll weevil[2] | 97 | 2 | 0.4 | --- | --- | --- |
| Boll worm[3] | 98 | 1.3 | 0.2 | --- | --- | --- |
| Cabbage looper[4] | 97 | 1.9 | 0.6 | --- | --- | --- |

* (After Himel and Moore, 1967, 1969) Fluorescent particle tracer system used.

1. Choristoneura fumiferana
2. Anthonomus grandis
3. Helothis zea
4. Trichoplusia ni

Table 2-6 **Major Components of Pesticides Losses in Spray Processes.**

1. Delivery losses ( 60 - 80 % of most sprays )
   a. Directly to the soil
   b. Peripheral foliage
2. Primary volatilization losses to the air
   ( 3 - 10 % of many sprays, but depends on volatility )
3. Primary particulate drift losses (in the air)
   ( 3 - 5 % of many sprays )

Table 2-7 **Terminal Velocity of Spheres (in Still Air)**
**( Reynolds number < 0.1 )***.

| Droplet Diameter μm | Fall Rate, (sp.gr = 1) m $sec^{-1}$ |
|---|---|
| 1 | 0.00003 |
| 10 | 0.003 |
| 20 | 0.012 |
| 50 | 0.075 |
| 100 | 0.275 |
| 200 | 0.721 |
| 500 | 2.139 |

* after Himel (1982)